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CALIFORNIA DIVISION OF MINES AND GEOLOGY

SPECIAL REPORT 124

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Special Report 124

OROVILLE, CALIFORNIA, EARTHQUAKE

1 AUGUST 1975

Edited by

Roger W. Sherburne

and

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CALIFORNIA DIVISION OF MINES AND GEOLOGY

1975

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FOREWORD

This Special Report is a collection of preliminary data collected by individuals from a number of public agencies and private organizations that are investigating the Oroville earthquake of 1 August 1975. We expect that additional data collected in the future will enable investigators to draw more definitive conclusions about the earthquake and its effects.

The Oroville earthquake was important because it took place in an area where most people did not expect an earthquake of such magnitude (5.7, Berkeley; 6.1, Pasadena). Many geologists and seismologists feel that this earthquake is a fair warning that earthquakes of magnitude 6 can occur anywhere in California and at any time, and that we should plan and design structures accordingly. California's 200 year history is too short to provide a complete record of all possible earthquake magnitudes and locations.

This report is organized into 4 sections. The first contains papers about the earthquake from the point of view of city and State officials, and the media. The second section discusses the geology and structure of the area. The third section discusses the damage that occurred in Oroville and surrounding area, and the fourth section discusses the seismology of the area, the earthquake, and its foreshocks and aftershocks.

Each author was requested to limit the length of his paper, and to submit it by October 15, 1975, in camera-ready form. The Division is grateful for the prompt and cheerful compliance with these stipulations that has enabled us to publish this report in less than 5 months from start to finish. I thank each of the authors.

Thomas E. Gay Jr.

Thomas E. Gay Jr.
Acting State Geologist

SECTION 1

GOVERNMENTAL RESPONSE AND NEWS COVERAGE

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SSONS LEARNED FROM THE OROVILLE EARTHQUAKE

MES E. SLOSSON Formerly State Geologist; currently Professor of Geology at Los Angeles Valley College, and Commissioner, Seismic Safety Commission, State of California

The Oroville earthquake on August 1, 975 was a surprise, because it occurred here the majority of scientists and the ublic would not normally have anticipated oderate earthquakes. In this respect it as similar to the San Fernando earthquake f 1971 and the Bakersfield-Tehachapi arthquake of 1952 in that faults not hen recognized as potentially active ere, in fact, active and produced sigificant earthquakes.

This may be the reason why, for both he San Fernando and the Oroville earthuakes, scientists and the news media imediately looked for some exotic cause, uch as Oroville Dam, rather than a funamentally sound scientific hypothesis. he elementary scientific hypothesis is hat California is basically geologically oung and will continue to undergo stress nd strain related to tectonic effects. arthquakes should be anticipated in alost any location in California. The maority will, of course, be situated on or ear the San Andreas Fault or its many ubsidiaries.

Immediately after the earthquake some eoscientists instantly judged this event o be related to the Oroville Dam and ake Oroville and may have, in part, nelected to consider the earthquake of 940 which occurred in the same region nd was of the same general magnitude. urther scanning of the historic data ndicates that over the past century a imited number of similar magnitude arthquakes have occurred along the estern foothill belt of the Sierra evada.

Thus, in considering this past history long with the rather sharply delimited opographic features related to the aults of the western Sierra Nevada oothills, the Oroville earthquake should e interpreted as related to the tectoncs or crustal strain pattern for this eneral region. Further, this strongly uggests that the fault zones of the estern Sierra Nevada foothills extending from Bakersfield to Chico should be reanalyzed with the consideration given o the 1940 and 1975 earthquakes in Butte County, the alignments of faults associated with topographic features or terrain, and the current "state-of-the-art" in both seismology and geology.

The Oroville earthquake suggests that this event is indicative of future earthquakes within the fault zones of the western Sierra Nevada foothills. If this hypothesis is reasonable, earthquakes of at least magnitude 6 should be anticipated and considered when design criteria is established for engineered structures.

The Oroville earthquake, even though a magnitude 6 event, caused relatively little damage because of the very short duration of strong shaking (4 to 5 seconds); indeed, this was an abnormally short duration for an earthquake of this magnitude. Had the strong motion shaking continued for a longer period of time, such as the approximately 12 seconds of strong shaking that occurred in the San Fernando earthquake of 1971, the damage could have been comparable to that sustained in San Fernando. Of course the losses would have to be scaled down to give consideration to the lower population density and the fewer number of engineered structures located within the area of strong shaking. Engineers and designers should be forewarned about this anomalous time duration factor in order that the duration of the 1975 earthquake will not be used as a factor in their designs.

The lessons learned from the Oroville earthquake are:

1. Earthquakes of at least magnitude 6 can occur almost anywhere within the State of California.
2. The seismicity, tectonics, and recent geologic history of the Sierra Nevada foothills should be reanalyzed utilizing current geoscientific data and technology.
3. An updated interpretation of California's seismic history and tectonics is needed to produce reliable data from which to determine the recurrence factor of fault activity and earthquakes.
4. We should not be mislead by the short duration of strong motion shaking related to the Oroville earthquake.
5. The damage incurred for a given magnitude earthquake appears to have

a direct relationship to the duration of strong motion shaking.

6. Ground rupture appears to be more likely than previously considered for earthquakes of magnitudes 5 and 6 as pointed out by this earthquake, the Galway earthquake in 1975, and the San Fernando earthquake in 1971.

7. Minimal ground rupture such as occurred in this earthquake may be more difficult to locate in open fields than in areas where roads, utilities and structures exist and thus may have been overlooked in the studies associated with the historical earthquakes.

8. Structures designed under modern codes and regulations perform better than older structures and the best performance was characteristic to those where quality control was required and practiced.

Reviewed by Michael R. Ploessel and Perry Y. Amimoto.

OROVILLE MEETS THE CHALLENGE OF A MODERATE EARTHQUAKE

By John D. Nolan
City Administrator
Oroville, California 95965

The geology section of the 1972 Survey Report, Oroville General Plan Study, noted the occurrence of an earthquake twenty-four miles northeast of Oroville in 1940 but concluded it was "an isolated event" with an assumed recurrence interval of 100 years. Nevertheless, the 1:20 p.m. earthquake of August 1, 1975, changed all of our thinking.

IMMEDIATE CONCERNS

Citizen Reaction

Following this event the City focused on two major concerns: Citizen reaction and immediate damage assessment. Many residents were experiencing their first earthquake and understandably were upset by the intensity of the earthquake and its aftershocks. Telephone circuits were overloaded, the local radio station was off the air for several minutes, and network news flashes reported Oroville as being rocked by sharp earthquakes causing partial destruction and evacuation of buildings, fires, and numerous injuries. Fears about the stability of the Oroville Dam, located eight miles above the City, created even more concern.

Oroville Mayor Robert A. Winston and Mr. Phil Johns of the Department of Water Resources issued statements shortly after local broadcasts were resumed. Residents were advised that the event had not damaged the 770 ft. earth-filled dam. In fact, such an occurrence would tend to consolidate and strengthen the dam. They also advised that only minor damage had occurred in the older commercial areas of the City and few injuries had been reported. The local news media rebroadcast these assurances and advised residents of pertinent safety information.

Meanwhile, regional and national newsmen coverged on the City. Local officials held a continuing press conference on the City Hall steps in an effort to correct earlier misconceptions about the damage. Direct contact was also established with major wire services through the Office of Emergency Services Headquarters in Sacramento.

Damage Assessment

Although no buildings collapsed, varying degrees of parapet and wall damage were reported. Fearing further damage from aftershocks, streets in the older downtown section were closed. Code enforcement, fire, and public works personnel continued preliminary inspections, and identified and barricaded high risk buildings. City inspection teams supplemented by two state inspectors continued their examination the next day. Professional engineering assistance was obtained through the local clearinghouse established by the Department of Mines and Geology and the Earthquake Engineering Research Institute. By agreeing to designate them as deputy building inspectors, the City obtained the volunteer help of structural engineers knowledgeable about earthquake damage.

Inspection criteria were established Saturday afternoon, August 2, based on the 1973 Editions of the Uniform Building Code and the Dangerous Building Codes then in effect in the City. Inspection forms supplied by EERI were reviewed and team assignments outlined on maps showing high hazard areas. Each team consisted of a licensed structural engineer, an engineering assistant, and representatives of the City's Code Enforcement, Public Works, and Fire Departments. Field surveys began Sunday morning and were completed early that same afternoon. In instances where access to buildings was not possible, the Park Department's aerial truck was used to lift inspectors to roof levels to check damage to walls, parapets, and roofs. Polaroid identification pictures were taken of each building and attached to inspection reports.

Following the field inspection, teams met with the Mayor and other City officials. Ratings in one of three categories were assigned to inspected structures: 1) The building was declared unsafe for occupancy and closed until a review by a civil or structural engineer was filed with the City and corrections to remove imminent hazards were completed. 2) The building contained certain hazards which did not directly endanger public safety but must be corrected according to an engineering report supplied by the owner within a specified time period. 3) No hazardous conditions were observed and no further investigation required at the present time.

This inspection provided professional evaluation of approximately thirty damaged buildings and determined which would not be open to the public on Monday, August 4. It also provided a review procedure for other commercial structures which continued with the help of engineers from the State Office of Architecture and Construction and building inspectors from the City of Marysville and Yuba County. House to house surveys by on-duty fire personnel began on Monday and pinpointed serious residential damage. In less than one week the preliminary assessment of earthquake damage had been completed.

INTERMEDIATE STEPS

Assistance

On Monday, August 4, the City Council confirmed the Proclamation of Emergency issued by the Mayor and requested state concurrence in the existence of an emergency. Office of Emergency Service personnel had been on site since Friday afternoon providing mutual aid assistance and advice on the types of emergency and financial help available.

Representatives of the Structural Engineers Association of Central California provided rosters of qualified personnel immediately available to assist property owners in evaluating their building for earthquake damage. They als provided the City with copies of emergency building standards adopted followin the 1969 Santa Rosa earthquake. Association representatives also attended public information sessions held by the City to allow residents and owners to hear reports on measures taken by the City and to ask questions about them.

Red Cross volunteers established a disaster assistance office in Oroville for emergency relocation measures. They also conducted preliminary damage surveys in unincorporated areas near the City.

Emergency Repair Standards

Standards for emergency repairs were needed immediately. The City Council hel several open meetings to secure input fro residents, property owners, engineers, and seismic safety experts. Following these meetings, the Council adopted procedures owners could follow to remove "red tagged" designations from their buildings. Interim guidelines were adopted September 4 following additional public meetings involving both citizens and technical people.

LONG TERM STANDARDS

Although both standards establish a six-month timetable for the adoption of guidelines for long-term use of buildings property owners were anxious to determine the ultimate repairs that would be required. The question of an "acceptable level of risk" has long been debated throughout the state. Faced with an identified fault zone in the vicinity of Oroville and the belief that events of a magnitude of 6 or larger could occur in the future, the Council authorized appointment of a 13 member citizens advisory committee to recommend criteria for long-range use of buildings. The broadly based committee consisted of building owners, tenants, bankers, realtors, builders, insurance brokers, and at-large members. Two Council members completed the committee. Staff was provided by the City Administrator, Fire Chief, and Code Enforcement Officer, and the City's structural engineering consultant. The standards suggested by the committee were reached after debate, discussion, and deliberation by each member. These standards were adopted by the Council on October 6, barely two months after the initial earthquake.

Throughout this period many individuals and organizations worked to meet the challenges and the problems that a moderate earthquake brings to a small community. Confident leadership by the Mayor and City Council combined with voluntary professional assistance and capable staff effort resulted in a thorough and reasonable program for earthquake recovery. The City has begun to solve some of the problems created by the earthquake. The foundation has been established, and prompted by the continuing aftershocks, Oroville begins the task of recovery.

ACKNOWLEDGEMENTS

Reviewed by Robert A. Winston and George C. Barr.

SUPPORT TO LOCAL GOVERNMENT

By: Lynn E. Roberts, Manager
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An earthquake in California can always become a major crisis, depending upon the magnitude and the location of the epicenter. In any emergency, the California Office of Emergency Services (OES) is prepared to assist local government protect life and property, restore public buildings, and aid the general public. Under California law, OES is tasked with: identification of areas where other state agencies, with the approval of the Governor, may assign resources not available at the local level; coordination of Federal Agency resources, if the situation warrants; and requesting mutual aid from adjacent local governments based on needs.

An analysis of a small earthquake near the City of Oroville may be helpful in recognizing the role of various levels of government in such an event. Although the damage there was minor, when compared to great earthquakes of the past, local government still had to face most of the problems associated with larger events. Because of the relative serenity, this event was an ideal situation in which to observe the California disaster aid mechanism in action.

After three small shakes in the morning, the major event took place at 1:20 pm, PDT, on the 1st of August, 1975. It registered 5.7 Richter at the Berkeley Observatory with an epicenter approximately 5 miles southwest of the City of Oroville. OES headquarters in Sacramento dispatched Mr. Warren Knieriem, Fire Coordinator, OES Region III, to the scene to contact local officials, determine damage, and assess the general situation. By 4:00 pm preliminary estimates of damage were sent to Charles Manfred, Director of OES. It appeared that damage was confined to the immediate vicinity of Oroville with no reported deaths and few injuries. However, the first problem was growing. News media representatives arrived in significant numbers. After seeing for themselves that the city was not in ruins and unable to locate bodies lying in the streets, they departed as quickly as they had appeared. Nevertheless, many inaccurate stories were printed throughout the country concerning the earthquake that day. One of the first actions constituting aid was a consolidated factual report prepared for the media by the OES staff.

Other state agencies: CHP, CALTRANS, State Police, Forestry, Office of Architecture and Construction, Department of Education, and Department of Health were tasked to evaluate the local situation with available personnel in the area and report to the Director of OES.

By 5:00 pm, Lynn E. Roberts, Regional Manager, OES Region III, had set up a field office at Oroville City Hall, where he met with Mayor Robert Winston, City Administrator John Nolan and the City staff.

It was apparent by this time that major damage was confined principally to a four-block section of downtown Oroville. City employees organized into teams under joint direction of the Building Inspector and Fire Chief and were systematically inspecting the city to identify hazards. Enough radio equipped vehicles to provide adequate communications were assigned to these teams from Police, Fire, and Public Works assets. By midnight it appeared that residential areas, in general, had endured the event rather well. Some downed chimneys presented a hazard, but little structural damage was evident. However, the downtown area was a different story where most buildings were brick structures dating back to the mid-1800's. Obvious cracks and wall separations, loose parapets and insecure footings were apparent throughout the four-block area. The County Courthouse Annex and some old schools appeared unsafe. As a consequence, evacuation of the four-block downtown area was completed.

It soon became apparent that the city's first priority should be to identify and prevent occupancy of hazardous structures. Research of City Ordinance confirmed that the city could legally condemn structures under the local hazardous buildings code. However, this was a task for structural engineers, and beyond the capabilities of the city's one building inspector. Luckily, four structural engineers were in the local area. Frank E. McClure, Structural Engineer, Oakland; Ted Canon; Chris Poland and John Lawder, all of H. J. Degenkolb and Associates, San Francisco, volunteered their services for two days. The city officially deputized them as Deputy City Building Inspectors for the period. Two cherry pickers, one loaned to the city by Pacific Telephone Company, were put at their disposal so inspections could be made from above as well as below buildings. City crews were then organized under the Fire Services and commenced a house-to-house inspection for damages in residential areas. By Sunday night ever dwelling in the city had been inspected and the occupants advised if hazards existed. By Sunday morning the American Red Cross ha organized local volunteers, primarily members of CB Radio Clubs, to assist them in conducting a house-to-house inspection in the unincorporated areas of the city.

By Sunday night the volunteer members had completed their inspection of the downtown areas an rendered a report to the city staff. They recommended that 17 buildings be declared unsafe and posted. Seven others probably could be occupied on a temporary basis, provided that repairs were effected within two weeks.

Reports had been consolidated by Monday morning and the Mayor declared an emergency and officially requested aid from the Governor. The Director of OES accepted, on behalf of the Governor, that a State of Emergency existed, allowing all state agencies to provide assistance to the city. OES Disaster Assistanc Director, Mr. Gordon Larkin, bega a formal damage assessment to determine if the dollar amount of damage was large enough to warran federal aid. The California Office of Architecture and Construction and the California Department of Education assigned engineers to inspect public buildings and schools.

Closure of the downtown buildings affected some 20 residents and displaced approximately 65 owners and/or employees. Monday night, the Mayor called a public press conference and announced th closures. This theme was to continue throughout the next week, with several public meetings chaired by the Mayor and/or City

Council in an attempt to create public awareness of their rationale in these actions. Probably, because of this, they were strongly supported by public opinion.

Temblors continued throughout the week, with near 5.0 Richter magnitude occurring on Tuesday and Thursday. With each aftershock, more structural damage appeared. The city was now faced with the task of reinspecting buildings that initially appeared sound. There were not enough hours in the day for the one Building Inspector to keep up, so a request for state aid was made. Lynn E. Roberts requested mutual aid from adjacent counties and cities. Sufficient inspectors arrived from the City of Marysville and Yuba County to complete the task.

Initial damage estimates were not of a magnitude to require massive federal aid through a Presidential Declaration. California State Statute precludes monetary aid to the private sectors in a disaster, so the OES Director requested aid through Mr. Robert Stevens, Region 9, Federal Disaster Assistance Director, from the Small Business Agency who have statutory authority to declare local disasters and offer low interest loans based on need. The request was approved and an SBA team set up a field office in space provided by the City of Oroville, where the SBA and ARC jointly interviewed local private citizens who requested aid.

The OES regional staff maintained a field office in the city for two weeks and continued to provide assistance to the city government. Close contact was maintained between the city and the ARC/SBA offices throughout the following months.

In summary, the actions of all levels of government in this event were commendable. Local government reacted reasonably at all times and a properly informed public strongly supported them. Control was maintained by the city government throughout the period and resources were assigned under a valid system of priorities. Although outside aid required was minimal, that which was provided was both timely and effective. Within one week the city was functioning normally, which can probably be attributed to the strength and dedication of both elected and employed city officials, supported by an informed public.

Reviewed by:

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OROVILLE QUAKE

By Joann Lee
KXTV News
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My camerawoman and I arrived in Oroville about 4:30 Friday afternoon. The town looked deserted--and the only hint of anything amiss was another news crew near City Hall, interviewing a local resident.

Further into the town signs that an earthquake had struck, became more apparent. Rubble and glass from shattered windows lined the streets, while sections of sidewalks were cordoned off. Otherwise, there was little else to indicate that a disaster may have occurred.

At City Hall, the mayor of Oroville filled me in on the amount of damage which had been reported to him. By now, I realized that earlier reports of burning buildings, hundreds of people hospitalized, and general chaos, were greatly exaggerated.

I felt my first aftershock shortly after entering City Hall. It could only be described as a series of quick, sharp jolts, lasting for about 20 seconds.

After calling in a live report for the 5:30 news cast, we drove around the town--mostly in the commercial areas--to assess damages. The hardest hit seemed to be a shoe shop. The glass front had collapsed, but no one was injured.

Next, we drove out to the dam. The crucial question was the condition of the dam--would it be in any way affected by the jolts.

It took awhile before we found out where to go, or even who was in charge of operations. But we finally reached the supervisor overseeing dam operations, and he supplied us with all the information he had.

One of the major problems we had throughout the assignment was, who to talk with. It was difficult to locate anyone who could tell us anything. Fortunately, we did run into three members of the California Division of Mines and Geology, later on in the evening. They were very cooperative, and provided us with a general view of the extent of damage throughout the city. During a filmed interview with state geologist James Slosson, I was able to get a pretty good working man's knowledge of the why's, and how's of an earthquake.

In general, I found that it was difficult to gather information, mainly because there was no one place, or person "in charge", and on top of things. However, members of the Division of Mines and Geology were in fact, very helpful, once I was able to get hold of them.

Telephone service was almost impossible. At one point, I had to stay on the phone with my station half an hour in advance of the news broadcast to make sure I would be able to get through.

The jolts continued throughout the night, and into the next day. Residents were uneasy, but except for the fear of another earthquake hitting, conditions seemed almost back to normal, by Saturday.

REPORT ON THE
OROVILLE, CALIFORNIA EARTHQUAKE
CLEARINGHOUSE

By R. Sherburne, J. Alfors, F. Bacon

INTRODUCTION

A moderate or large earthquake provides an opportunity for engineers and earth scientists to reaffirm old ideas and gain new insights relative to earthquake damage and generation. Although the number of people investigating an earthquake and the quantity of instrumentation may appear very great to local population, it is seldom that sufficient resources are available so that all of the goals of an earthquake investigation are accomplished. With limited resources better planning is needed.

For nearly a decade the notion of an earthquake clearinghouse has been discussed as an important post-earthquake activity; important because it can avoid duplication of effort by scientists and engineers, improve the understanding of earthquake-induced damage to engineered structures, and ultimately result in improved seismic safety.

The evolution of the clearinghouse activity, the operations of the Oroville clearinghouse, how to find the next clearinghouse, and features to be considered for improving future clearinghouse operations will also be discussed in this paper.

PAST CLEARINGHOUSES

Although the concept of a clearinghouse has been in existance for some time, only two formal clearinghouse operations have been conducted within California. Following the San Fernando earthquake (M~6 1/2, 9 February, 1971) and the Point Mugu shock (M~5 3/4, 21 February 1973), the Los Angeles District of the California Division of Mines and Geology (CDMG) and the Earthquake Engineering Research Institute (EERI) cooperated to establish a clearinghouse activity; prior to the termination of each of those acitivities a meeting of concerned engineers and geoscientists was held to dispense information relative to identified hazards, damage, and geoscience investigations. The clearinghouses for those earthquakes were established at the CDMG Los Angeles District Office and at a suite of motel rooms in Oxnard, Ventura County, respectively.

It was not until the publication of the First Report of the Governor's Earthquake Council (1972) that general guidelines describing the clearinghouse functions were available. The EERI publication Learning From Earthquakes (1975) contained suggestions pertinent to the information that should be collected at a clearinghouse. The role of a clearinghouse is to provide a location at which scientists, engineers, and governmental representatives may meet and learn what others have observed during the early post-earthquake investigative activities. The dissemination of this information avoids duplication of effort, may indicate the need for additional studies, and may also provide the data base necessary for efficient recovery operations.

OROVILLE CLEARINGHOUSE

At 1320 PDT on 1 August 1975, a magnitude 5.7 earthquake occurred approximately 10 km southeast of Oroville. Surface rupturing along the west flank of Cleveland Hill 8 km east of Palermo has been associated with this earthquake, and this break has been named the Cleveland Hill fault. It has been postulated to be a normal fault with a surface expression that trends nearly parallel to the western margin of the Sierra Nevada Mountains. This earthquake was significant for several reasons, but in particular it provided an opportunity to initiate, operate, and evaluate a clearinghouse without the complications of excessive post-earthquake activity.

The Sacramento District Office of the CDMG made arrangements with the California Division of Forestry to establish a clearinghouse at the Butte Ranger Unit Headquarters in Oroville. These arrangements were completed at 1550 PDT 1 August 1975; the clearinghouse was staffed the following morning at about 0745 PDT. Several features made this site an excellent choice; the cooperation and congeniality of the Forestry personnel were a significant contribution to the ease of the clearinghouse operation, the accommodations provided were excellent (space, communications, etc.), and the location was accessible and easily located by incoming investigators.

The most important activities of the clearinghouse were the compilation of information relative to damage, instrument deployment and field investigations in the area and maintaining an active file as to where the scientists were residing if more than a day long stay in the area was expected. Maps were used for the first two items and a sign-in sheet was maintained for the last. This information was used to avoid duplication of effort and to indicate areas which had not been examined. A modified version of the clearinghouse visitor's sign-in list is shown in Table 1. Those investigators not visiting the clearinghouse, but making contact with the clearinghouse are not cited in Table 1.

It is important for local government to be informed of investigations which are being performed within the affected area. In some cases it may be possible to expedite estimation of damage, and in some instances local government may require the assistance of the professional people in the area to aid with certain phases of the recovery process.

FUTURE CALIFORNIA CLEARINGHOUSES

To facilitate the exchange of information, it is important that EERI and the earth scientists maintain clearinghouses that are spatially close -- preferably in the same room. The CDMG will try in future emergencies to obtain clearinghouse quarters through other State governmental agencies (Forestry, Highways, State Highway Patrol, Office of Emergency Services, etc.). Normally the responsibility for establishing and operating the clearinghouse would fall to the District Geologist in the CDMG district in which the earthquake occurs, if that office is still functional (see Figure 1). The address and telephone numbers of the clearinghouse may always be obtained from the CDMG headquarters in Sacramento, if functional. If a moderate (M~5.5) or greater earthquake were to occur in a district and the district office was functional, then the clearinghouse address and telephone numbers may be obtained from the District Geologist. If the shock were to disrupt the District Office, then the following scheme will be applicable:

Disrupted District	District to Contact
Sacramento	San Francisco
San Francisco	Sacramento
Los Angeles	Sacramento

Because communication lines to the CDMG offices may become overloaded or even disrupted following an earthquake, the location of the clearinghouse may also be obtained by calling the headquarters of the Office of Emergency Services in Sacramento. All of the pertinent telephone numbers are shown in Figure 1.

FUTURE CONSIDERATIONS

Although some deficiencies were noted in clearinghouse activities, most of these can be easily remedied, with the exception of contact with field personnel. It is very important that those people conducting field investigations put in an appearance to indicate the areas examined, areas to be examined, and to indicate their findings. At future clearinghouses, observations should be numerically coded on a map and entered in a notebook rather than compiled directly on a map as was done for the Oroville earthquake; this will facilitate the copying of the notes for later dispersal at the closing meeting. It is suggested that a common map be used for compiling damage and geologic data -- although this may not always be possible. Supplies of pertinent AAA and USGS topographic maps are rapidly depleted following a moderate or larger earthquake. It is not the responsibility of the clearinghouse to maintain a supply of maps, and investigators should bring their own maps for field use. It is very important for the earth scientist to have early information relative to the main shock epicenter and the early aftershocks; this information assists in the planning needed relative to instrument distribution, and aids the geologists when searching for tectonic rupturing. For a larger event with more damage, one person at the clearinghouse is not sufficient, particularly during the early hours of operation. To speed information dispersal, meetings should be held at the clearinghouse following each day's activities.

ACKNOWLEDGEMENTS:

Reviewed by Quintin Aune and William Wells.

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TABLE 1

Clearinghouse
Sign-in List
Oroville, California Earthquake
2 August 1975

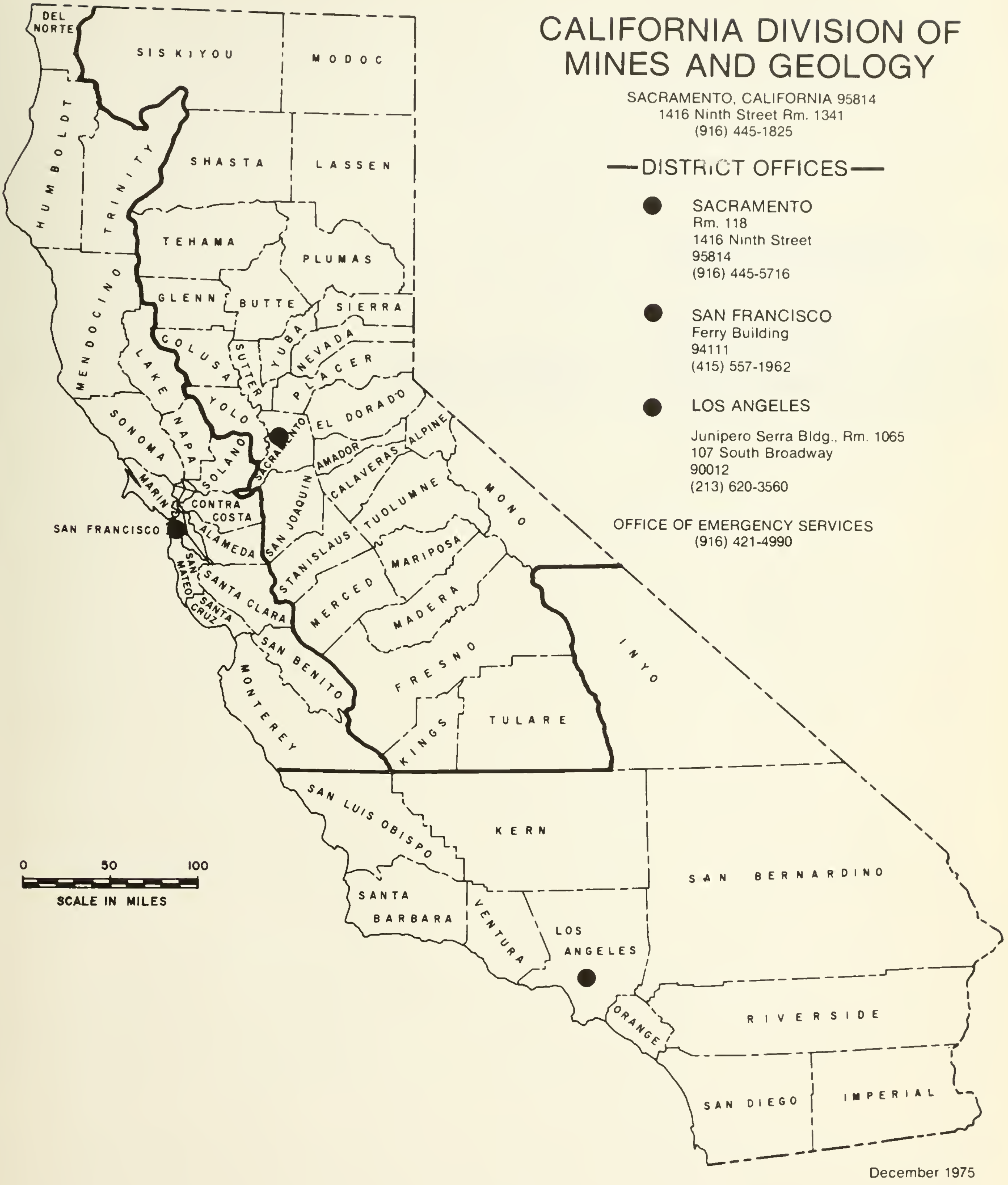
Investigator	Affiliation	Field of Expertise	Investigative Activity	Instrumentation
Hanks, T.	U.S. Geological Survey Menlo Park, Calif.	Ground motion	Strong motion	SMA-1 (Strong motion seismograph)
Relles, R.	Calif. Institute of Tech. Pasadena, Calif.	Ground motion	Strong motion	SMA-1 (Strong motion seismograph)
Knudson, C.	U.S. Geological Survey San Francisco, Calif.		Strong motion	
Lawder, J.	H.J. Degenkolb & Assoc. San Francisco, Calif.	Structural Engineering	Structures	
Canon, T.	H.J. Degenkolb & Assoc. San Francisco, Calif.	Structural Engineering	Structures	
Poland, C.	H.J. Degenkolb & Assoc. San Francisco, Calif.	Structural Engineering	Structures	
Aune, Q.	Calif. Div. of Mines & Geo. Sacramento, Calif.	Geology	Field geology	
McClure, F.	Earthquake Eng. Research Institute Oakland, Calif.	Structural engineering	Structures	
Tocher, D.	Woodward-Clyde Consul. Oakland, Calif.	Seismology, geology	Aftershocks, focal mechanisms, surface faulting	4 MEQ800 (microearthquake seismograph)
Johnson, P.	U.S. Geological Survey Menlo Park, Calif.	Precursory seismology		

TABLE 1 (continued)

Investigator	Affiliation	Field of Expertise	Investigative Activity	Instrumentation
Wood, M.	U.S. Geological Survey Menlo Park, Calif.	Precursory seismology	Precursive changes in tidal gravity measurements	Tidal gravimeter
Roberts, L.	Off. of Emerg. Serv. Regions III & IV Redding, Calif.	Observer emergency operations		
Dickey, W.	Masonry Institute of Amer. Los Angeles, Calif.	Structural engineering (masonry)		
Amrhein, J.	Earthquake Eng. Research Institute Los Angeles, Calif.	Structures (masonry & concrete)	Structures	
McLean, R.	McLean & Schultz Fullerton, Calif.	Structures		
LaGesse, H.	Calif. Div. of Mines & Geo. Sacramento, Calif.	Instrument installation	Strong motion	SMA-1 (Strong motion seismograph)
Wells, W.	Calif. Div. of Mines & Geo. Sacramento, Calif.	Geophysics	Strong motion	SMA-1 (Strong motion seismograph)
Toppozada, T.	Calif. Div. of Mines & Geo. Sacramento, Calif.	Seismology	Strong motion	SMA-1 (Strong motion seismograph)
Moran D.	Earthquake Eng. Research Institute Los Angeles, Calif.	Structural engineering	EERI Reconnaissance team	
Equchi, R.	Univ. of Calif. at Los Angeles Los Angeles, Calif.	Earthquake risk (student)		
Duke, C.	Dept. of Eng., Univ. of Calif. at Los Angeles Los Angeles, Calif.	Civil & earthquake eng.		

TABLE 1 (continued)

Investigator	Affiliation	Field of Expertise	Investigative Activity	Instrumentation
Harpster, R.	Woodward-Clyde Consul. Oakland, Calif.	Geology	Reconnaissance	
Taylor, G.	U.S. Geological Survey Menlo Park, Calif.		Seismology	Ten short period seismographs
Bufe, C.	U.S. Geological Survey Menlo Park, Calif.	Geophysics	Seismology	
Kroeger, H.	City of Oroville	Dept. of Public Works		
Bacon, F.	Calif. Div. of Mines & Geo. Sacramento, Calif.	Geology	Field Investigation	
Tanner, D.	Calif. Institute of Tech. Pasadena, Calif.	Instrumentation		Four 5 second trailer mounted seismograph systems
Andrews, D.	U.S. Geological Survey Menlo Park, Calif.	Observation		
Nolan, J.	City of Oroville	Administrator		



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December 1975

Fig. 1. The telephone numbers necessary to locate the CDMG-EERI earthquake clearinghouse are shown in this figure together with the CDMG districts.

SECTION 2

GEOLOGY AND GEOLOGIC INVESTIGATIONS

GENERALIZED GEOLOGY OF THE OROVILLE EARTHQUAKE AREA

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INTRODUCTION

During the course of the post earthquake investigation commencing with the afternoon of 1 August, 1975, it became clear that many of the surface effects observed as well as the other earthquake-related phenomena experienced by the local residents were characterized, in general, by the type or sequence of rocks underlying the individual observation sites. In addition, correlation of effects and general field investigation procedures were hampered, to a greater or lesser degree, by the unavailability of recent geologic mapping of the investigation area.

This paper is designed to serve as a preliminary summary of the geology of the area with the primary emphasis being placed on the areal distribution and description of the characteristic properties of the various rocks.

As a minimum of field time was available for original surveying or field checking of reported observations, the data used in the compilation of this report were taken mainly from Lindgren and Turner (1895), Turner and Lindgren (1895), Turner (1898), and Lindgren (1911).

In some cases, reinterpretations of distribution and stratigraphy were made based on field observations and topographic evidence as well as on data presented in reports of more detailed investigations of selected areas (California Department of Water Resources, 1963; Creely, 1965).

The geology described herein has been summarized in Fig. 1, which covers portions of the Oroville, Big Bend Mountain, Bangor, and Gridley 15' quadrangles.

GEOLOGY

Lindgren and Turner (1895) grouped the rocks of the Sierra Nevada into two distinctive suites which they named the Basement Series Rocks, consisting of the steeply eastward to vertically dipping and intensely folded and faulted metamorphosed sedimentary and volcanic rocks and associated igneous intrusives, and the Superjacent Series, consisting of the late Cretaceous, Eocene, Neocene (Miocene and Pliocene), and Pleistocene sedimentary and volcanic rocks which unconformably overlap the Basement Series rocks.

Within the area discussed in this report (see Fig. 1), excellent exposures of these rocks are to be found; the older rocks being represented in the eastern portion of the area and the younger sedimentary rocks in the western part.

Crystalline Basement Series Rocks

The basement series rocks underlie the entire eastern portion of the area with surface exposures extending as far west as Thompson's Flat, south of South Table Mountain, and south along a north-northwesterly trending front passing just east of Palermo.

Throughout the central region, the basement rocks are overlapped by the younger Superjacent Series sedimentary rocks through which outcrops of the basement rocks occur sporadically and generally with relatively minor areal extent.

On the basis of lithology, the basement rocks can be separated into three distinct northwest trending units or belts which include (from west to east): 1) Upper(?) Jurassic metavolcanic and metasedimentary rocks typified by local massive outcrops sub-rounded to sub-angular in form, 2)

Paleozoic(?) amphibole schists typified by local, foliated tombstone-like outcrops and 3) Upper(?) Jurassic granitic intrusives that crop out as massive blocks in the eastern hills. These units have been differentiated in Fig. 1 and will be discussed below in their proper sequence.

Paleozoic(?) metavolcanic rocks

In their investigation of the Smartsville Folio, Lindgren and Turner (1895) described an extensive suite of schistose to massive amphibolite which they believed to have been derived from a varied assemblage of basic igneous rocks.

In later investigations in nearby areas, Turner (1898) and Creely (1965) reached similar conclusions.

In the investigations mentioned above, textural variations ranging from massive to schistose were encountered, however, within the area shown in Fig. 1, the schistose variety is prevalent and has been mapped by Lindgren and Turner (1895) as the "Amphibolite Schist" and by Creely (1965) as the "eastern belt" of "unnamed metavolcanic rocks". For this report, the term "Amphibolite Schist" has been retained.

When fresh, the amphibolites appear dark green to bluish-gray and are composed of a usually fine-grained aggregate of albite, epidote, and minor chlorite in association with actinolite, the secondary amphibole. Other minerals present in lesser amounts include clinozoisite, sphene, calcite, magnetite, and pyrite (Creely, 1965).

The composition of the rocks have been discussed in detail by the above investigators (Lindgren and Turner, 1895; Creely, 1965), and the reader is referred to those reports for information beyond the summary contained herein.

The amphibolites have been shown in Fig. 1 as being questionably of Paleozoic age as based on the interpretation of Creely (1965) who considered the rocks to be roughly correlative with the nearby Calaveras Formation. He suggested that due to their relation with the adjacent much less deformed Oregon City Formation (Upper Jurassic), that the two rocks were in fault contact along a major east-dippin thrust. This fault has been shown in Fig. 1 to separate the amphibolites from the Oregon City Formation in the northern portion of the map area, and will be discusse in more detail below in the section on structure.

Lindgren and Turner (1895) were uncertain of the age of the amphibolites and showed them to be, simply, of pre-Carboniferous age; a conflict was, however, presented in their interpretation in that they believed the amphibolites graded into the adjacent "porphyrites" and "diabase" to the east and west which were shown as "Post-Carboniferous."

The western "diabase" of Lindgren and Turner was mapped in the Oroville quadrangle as the Upper-Jurassic Oregon City Formation by Creely.

Upper Jurassic(?) metavolcanic rocks

Exposed to the east and west of the amphibolite schist are the metamorphosed volcanic and sedimentary rocks mapped by Lindgren and Turner (1895) and Turner (1898) as "porphyrites" and "diabase." In the north-central portion of the map area (Fig. 1), the western exposures of these rocks were mapped by Creely (1965) and separated into two units termed the Oregon City Formation and Monte De Oro Formation.

The term Oregon City Formation has been tentatively applied to the exposures of metamorphosed flows, pyroclastics and volcanic-sedimentary rocks of the amphibolite schist described above. The Monte De Oro Formation (of Creely) has been retaine with the only currently known exposure occurring in the north-central portion of the map area (Fig. 1) as mapped by Creely (1965).

To the southeast, the northern tip of a relatively large distribution of "greenstone" is exposed near the town of Bangor and is possibly equivalent to the Oregon City Formation. In lieu of a precise correlation, the term "diabase" of Lindgren and Turner (1895) has been retained for the southeastern "greenstone."

The oldest unit of the rocks thus exposed is the Upper Jurassic Oregon City Formation of Creely (1965), which is composed of a wide variety of intermediate to basic pyroclastic rocks with subordinate flows and volcanic-sedimentary rocks of similar composition. The original rock types were determined by Creely to include tuff to tuff breccia with the lithic fragments ranging in size from a fine-grained tuff to lapilli tuff and commonly containing bombs or blocks of amygdaloidal rocks frequently attaining dimensions of as much as 2-1/2 feet.

Where non-fragmental, the rocks are commonly porphyritic with altered phenocrysts of augite and plagioclase set in a fine-grained matrix consisting primarily of "saussuritized" plagioclase and "chloritized" ferro-magnesian minerals (Creely, 1965).

The Oregon City Formation is distributed throughout the central portion of the map area with exposures to the north near Oroville and to the southwest of the Tertiary conglomerates in the south-central portion of the area.

Through the central portion of the belt, southeast of Oroville, the formation is covered by Tertiary sedimentary rock. Irregularly sized outcrops occur here and are generally of minor areal extent. Throughout this region, the contact with the amphibolites is covered and the contact cannot be readily determined. It is believed, however, that the fault contact as described by Creely (1965) is valid and extends south beneath the sedimentary cover to separate the Oregon City Formation from the amphibolites. The amphibole schist tends to be highly foliated and sheared near the contact.

Exposed at the extreme northern portion of the area is a small outcrop of metamorphosed rocks named, by Turner (1896), the Monte De Oro Formation. This formation consists of dark, well indurated sandstone, siltstone, conglomerates and slates of Upper Jurassic age.

These rocks bear a close resemblance to the Logtown Ridge Formation to the south along the Consumnes River with which a correlation was suggested by Creely (1965).

As exposed in the Oroville area, the rocks of the Monte De Oro Formation represent the faulted off core of a tightly folded syncline with the older Oregon City Formation flanking the rocks on both sides (Taliaferro, 1942).

Upper Jurassic granitic intrusives

Along the eastern portion of the area, the terrain is underlain by a granitic mass of considerable size which has been described by Lindgren and Turner (1895) and Turner (1898).

The above investigators found the composition to vary, but consist predominantly of quartz and plagioclase feldspar with relatively minor amounts of mica. The granitic rocks range from quartz-diorite to diorite with lesser amounts approaching a true granite in some locations while in others it approaches a gabbro-diorite.

In the Bidwell Bar Folio, Turner (1898) interpreted the northerly continuation of the rocks represented in Fig. 1 to be in normal intrusive contact with the surrounding older sedimentary and volcanic rocks. Within the area shown in Fig. 1, the exact nature of the contact is less clear with the pronounced linearity of the amphibolite-"granite" contact east of Wyandotte and a prominent change in elevation across the contact suggesting the possibility of a north-northwest trending fault.

This possibility will be dealt with more completely in a later section of the report.

Superjacent Series Rocks

Within the area under discussion, rocks of the superjacent series represented in outcrops, include the Tertiary Ione and

Mehrten Formations which are more common further to the south along the foothills, as well as several younger, more dissected and locally derived units.

Presumably, underlying the Cenozoic sediments in the western portion of the area are the Upper-Cretaceous Chico Formation and the Eocene "Dry Creek" Formation. As far as is currently known these rocks are in the subsurface only within the area shown on Fig. 1, however, Creely (1965) described small exposures of these rocks in the vicinity of North Table Mountain several miles northwest of Oroville.

Ione Formation

The Ione Formation was named by Turner (1894) for a distinctive sequence of light colored quartzose sandstone, clay, siltstone and minor conglomerate distributed along the western flank of the foothills.

Since Turner, the most significant investigations of the Ione were undertaken by Allen (1929), who limited the term "Ione" to the lower clay and sand units of Turner. Pask and Turner (1952) separated the formation into two members differing in mineralogy. The upper "clay rock" unit of Turner has since been termed the (Miocene) Valley Springs Formation (Piper, et al, 1939).

In the Oroville area, the Ione Formation has been described briefly by Turner (1894) and Lindgren (1911).

The most significant exposures of the Ione Formation in the Oroville area occur in the vicinity of South Table Mountain (near the northern border of Fig. 1) and North Table Mountain (just off the map area to the north). In this vicinity, the Ione was observed to lie stratigraphically between the "Dry Creek" Formation and the (Miocene(?)) Mehrten Formation and consisted primarily of "light colored argillaceous sandstone and claystone... [with] subordinate amounts of siltstone, shale, and conglomerate [and] minor amounts of lignite" (Creely, 1965).

Characteristically, the Ione sediments weather to a subdued, soil covered, gentl rolling landform. Usually, quite easily recognizable, the Ione Formation is typically white to buff colored with both the sands and clays frequently stained red, orange or yellow. In both cases, bedding is usually poorly defined with many portions being more properly termed "massive". The most commonly observed structural feature observed is crossbeddi which sometimes occurs with large dimensi

The sandstone is composed, predominant of angular to sub-angular moderately sort quartz and minor feldspar, epidote, zirco tourmaline, and andalusite, with the kaolinitic clays acting as the cementing agent. Frequently, the sands contain sma "pearly" flakes of micaceous looking kaolinite (Creely, 1965).

The most abundant form of the Ione Formation present in the area are the cla which vary from white to gray and are usually interbedded with the sandstone. The clay is usually massive and "blocky" but usually soft and somewhat plastic (Creely, 1965).

Mehrten Formation

In this report, the term "Mehrten Formation" is used in the same sense as used by Creely (1965). Within the area represented by Fig. 1, the formation crops out mainly within the area mapped by Creely and the major portion of the summary contained herein was taken from that report.

In the vicinity of North and South Tabl Mountains, a sequence of andesitic tuffs was originally mapped on a provisional basis, as the Mehrten Formation. At this locality, the rocks were observed to stratigraphically lie between the older Ione Formation and the overlying basalts. To the east and northeast of Oroville, two occurrences of minor areal extent have bee shown in Fig. 1 on the basis of preliminary observations made during the post-earthquake investigations. Here, the exposures represent fensters through the younger Tertiary conglomerates and indicate the probability of a much greater distribution of the rocks than originally suggested by the known exposures.

As described by Creely, the dominant rock types in the area are andesitic lapilli tuff to tuff breccia, frequently interbedded with shale and sandstone.

In both pyroclastic units, the lapilli and rock fragments range in size from 1 1/2 inch to 3 inches and are set in a matrix containing considerable amounts of silt, clay, and larger grained crystals, lithic, and vitric fragments.

The formation is characteristically light in color - ranging from light gray to medium brownish gray and the exposures are moderately to well indurated.

The age of the formation in this area has been shown to be Miocene on the basis of K-Ar dating of the tuffs at South Table Mountain (Dalrymple, 1964).

Lovejoy Basalt

The most prominant topographic features in the Oroville area are the twin mesas of North and South Table Mountain. South Table Mountain lies northwest of Oroville near the northern margin of Fig. 1 and is the result of differential erosion due to a protective capping of basalt which was described by Turner (1894) as "Older Basalt".

In the Oroville quadrangle, Creely (1965) retained the terminology of Turner for the basaltic flows capping Table Mountain as well as for lesser exposures east of Oroville.

In his regional study of the Tertiary basalts of the Sierra Nevada, Durrell (1959) applied the term "Lovejoy Basalt" to the basalts described as "older basalts" by Turner and applied this term to the basalts of Table Mountain. In this report, the terminology of Durrell has been maintained.

At South Table Mountain, the rocks are black, hard, fine-grained microcrystalline to "slightly porphyritic" olivine basalt with phenocrysts of plagioclase and minor augite set in a hypocrystalline groundmass of varying composition (Creely, 1965).

Stratigraphically, the basalts overlie the Mehrten Formation with angular unconformity and physically overlap several of the older Tertiary units of the area. Dalrymple (1964) obtained a K-Ar age determination of 23.8 m.y. for the Mehrten Formation immediately underlying the basalts at South Table Mountain and a similar date of 22.2 m.y. for samples of the Lovejoy Basalt near Blairsden. With this information, an age of lower Miocene was applied to the basalt (Dalrymple, 1964, Creely, 1965).

"Tertiary conglomerates"

Throughout the central portion of the area, the most extensive unit exposed is a sequence of variably(?) aged gravels which overlie and obscure the earlier Tertiary and older basement series rocks. As used here, the term, "Tertiary conglomerates" is assigned to the informal unit of undifferentiated Pliocene and earlier(?) alluvial fan and stream deposits mapped by Lindgren and Turner (1895) as the "auriferous gravels" and "shore river gravels" and includes the upper of two upper "rolling benches" of Lindgren (1911). In part, the Tertiary conglomerates" are equivalent to the Red Bluff Formation as described by Creely (1965).

The term "auriferous gravels" has been avoided inasmuch as most of the gravels of the area were extensively placered for gold. As expressed by Chaney (1933), the auriferous gravels of the Sierra Nevada range in age from Eocene (or possibly even Upper-Cretaceous) through Pleistocene. This must be extended to include Holocene, as well.

The "Tertiary conglomerates" as seen in the Oroville area are comprised of quartz, volcanic, greenstone, and siliceous metamorphic cobbles set in a sandy matrix derived from similar rocks and include intertonguing layers of conglomerate, pebbly sandstone, and sandstone. The rocks are poorly consolidated and where exposed, the older more weathered gravels crumble easily when struck with the hammer.

The thicker accumulations in the area probably approach 150 feet and variably overlie the entire sequence of rocks previously described. Characteristically, the rocks are stained a reddish brown to orange and form the gently rolling dissected uplands with a shallow rocky soil cover and a usually moderate to heavy growth of grass and oak.

The main mass of gravels extending north-south down the center of the map was deposited on a relatively smooth erosional surface. Clasts show a great variety in composition and the gravels probably represent ancestral Feather River alluvial fan deposits. The belt of gravels extending southeast near Bangor contains only minor chert and shows a lesser variety of clast compositions. It is suggested that these gravels were deposited in a deep narrow canyon approximating the modern topographic relief.

These gravels may represent an accumulation of aggrading stream deposits from an ancestral Honcut Creek.

Plio-Pleistocene rhyolitic tuff.

Sporadically exposed throughout the western part of the area are outcrops of limited areal extent of a distinctive pumice lapilli tuff and tuffaceous sediments that were described by Creely (1965) as the "Unnamed Rhyolitic Pumice Tuff". In the Oroville area, these rocks have been previously described by Lindgren (1911) as the "Tuffs of Oroville".

As described by Creely, in one outcrop area, the tuffs are composed predominantly of rhyolitic to andesitic vitric tuff with "interstratified layers containing abundant lapilli of white pumice". Characteristically, the tuff is light colored, ranging from white to light gray or buff and commonly stained orange to reddish brown.

The largest exposures in the area are found north and east of Oroville and appea to be interbedded with the "Tertiary conglomerates" described above.

At the time of writing, no source has been definitely attributed to the tuffs. Lindgren (1911) suggested that the source was the Marysville Buttes to the southwest in the Sacramento Valley. The Marysville Buttes are now generally considered to have been a true volcano (in the extrusive sense of the term).

The rocks of the Buttes range from rhyolitic to andesitic (Williams, 1924) in composition and, in general, tend to suggest correlation with the Oroville tuff

Creely (1965) considered the posibility of correlating the Oroville tuff with the Nomlaki Tuff member of the Tuscan Formation to the northwest, but rejected the concept on the basis of indistinct mineralogical similarities as well as the considerable separation between exposures.

The age of the tuff was considered by Creely (1965) to be of late Pliocene, however, on the basis of their relation with the "Tertiary conglomerates," it is suggested that the age may be extended to include the lower Pleistocene.

Pleistocene terrace deposits.

Along the western flank of the hills in the central portion of the area, a system of Pleistocene terrace deposits have been differentiated primarily on the basis of geomorphic evidence which has been interpreted as suggesting at least three distinct steps or terraces above the present floodplain level of the Feather River. The terraces are underlain by poorly consolidated deeply red stained gravel, sand, silt and clay similar to the variabl overlying Holocene alluvium. Shallow exposures of the various terrace units are provided by roadcuts throughout the area.

As differentiated, the terraces are separated on the basis of elevation above the flood plain (which may be considered a fourth and youngest terrace) as well as by the extent of soil development on the surfaces of the units.

The youngest terrace differentiated (Qt-1) lies an average elevation of about 40 feet above the present flood plain and shows the greatest similarity to the modern alluvium. Lindgren (1911) suggested a similar system, however, with two primary levels. The 40-foot terrace would correlate with the 160-foot terrace of Lindgren (Lindgren's terrace elevations were taken with respect to sea level).

The second terrace lies about 100 feet above the flood plain and was included in the lower of Lindgren's two upper "rolling benches". The oldest terrace lies at an elevation of about 140 feet above the flood flood plain and was also included in the lower of Lindgren's two upper "rolling benches".

In the Oroville quadrangle, Creely (1965) included the terraces as part of the Red Bluff Formation.

Alluvium.

Underlying the greater part of the western portion of the area is the extensive alluvial cover of the Sacramento Valley and alluvial and flood plain deposits of the numerous streams which drain the hills to the east.

These modern deposits consist primarily of a reddish clayey loam and black humus soil with abundant unconsolidated sand, silt, clay and gravel (Lindgren and Turner, 1895; Creely, 1965).

Throughout the area, the relatively thin deposits variably rest upon the older rocks with an expectedly pronounced unconformity, except in the case of the conformably underlying Pleistocene alluvial deposits which they resemble (Lindgren and Turner, 1895).

Within and along the base of the hills, many of the streams have been extensively placer mined and the tailings thus derived have been included in this unit in Fig. 1. These tailings have been used, in recent years, as an economical local source of aggregate.

Structure

Typical of many areas along the foothills of the Sierra Nevada, the structure of the Oroville area is the result of a complex geologic history. Many aspects of this history are still not clear.

Unfortunately, space does not permit an adequate discussion of the structure of the area and the reader is referred to the discussion in Creely (1965).

As previously intimated, the older bedrock series has been subjected to an intense deformation during which the rocks were variably dynamically metamorphosed. Intense folding was produced as evidenced in the area by the steep eastwardly dipping northwest striking isoclinally folded Oregon City and Monte De Oro Formations. In the northern portion of the area, the Monte De Oro Formation is exposed in the core of a tightly folded syncline with the Oregon City Formation flanking the Monte De Oro to both the east and west. The Monte De Oro Formation has been truncated both on the south and west, preempting the continuation of that unit to the south (Creely, 1965). A continuation of the complementary anticline to the east is suggested by the presence of the amphibolite schist, the oldest rocks in the area, which probably occupied the core and have since faulted into juxtaposition with the Oregon City Formation.

In the subsurface, the granitic intrusives may extend to the west under the metavolcanics at relatively shallow depth. However, at the present time there is no definite information to confirm this. Examination of the topography across the mapped area reveals a marked increase in elevation to the east across the granitic-amphibolite contact and has been interpreted as suggesting the presence of an easterly fault boundary for the amphibolite. In addition to the change in elevation, the linear nature of the contact further suggests the possibility of a fault.

Creely (1965) interpreted the western amphibolite contact as an easterly dipping thrust, indicating a truncation of the anticline.

As of the time of writing, due to the relatively poor surface effects created during the earthquakes of August and September, 1975, there is still some discussion as to the location of the fault along which the temblors originated. By far, the most convincing feature suggested is the newly named Cleveland Hill fault described elsewhere in this publication (Fig. 1).

To the west, the Cenozoic sedimentary rocks overlap the older basement rocks and have undergone only extremely minor deformation. For the greater part, the beds are relatively planar in attitude and dip gently west to southwest. They strike roughly parallel to the northwesterly structural trend.

Further insight into the structure of the area may be obtained as a result of a gravity investigation, currently in progress by the writer, of a greater portion of the area shown in Fig. 1.

ACKNOWLEDGMENTS

I would like to extend my thanks to Quintin A. Aune (C.D.M.G.) who helped in the compilation of the map and organization of data contained in this paper and to John T. Alfors and Roger H. Chapman for their expedient review and comments. Special thanks must be extended to Beryl Adrian for the typing of the final draft.

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EXPANDED LEGEND

(Qal)- Holocene stream channel, flood plain, and dredge tailings deposits.

(Qt-1)- 50 ft. terrace gravels: lower terrace gravels of Lindgren (1911); part of Red Bluff Fm. of Creely (1965).

(Qt-2)- 100 ft. terrace gravels: lower of two upper "rolling benches" of Lindgren (1911), included in Red Bluff Fm. of Creely (1965).

(Qt-3)- 140 ft. terrace gravels: may be included in lower of two upper "rolling benches" of Lindgren (1911), may be equivalent in part, to Red Bluff of Creely (1965).

(Tvr)- Rhyolitic to andesitic pumice lapilli tuff.

(Tc)- Pliocene and earlier(?) dissected alluvial fan and stream deposits, undiff.: includes upper of two upper "rolling benches" of Lindgren (1911), equivalent, in part, to Red Bluff Fm. of Creely (1965), includes "Auriferous river gravels" and "Shore river gravels" (exclusive of tuff component) of Lindgren and Turner (1895).

(Tvl)- Lovejoy basalt of Durrell (1959), "older basalt" of Creely (1965) and Turner (1894): microcrystalline to slightly porphyritic olivine basalt (K-Ar 22.2 m.y.).

(Tvm)- Mehrten Fm: Andesitic mudflow, lapilli tuff to tuff breccia, volcanic sandstone, congomerate. (K-Ar 23.8 m.y.).

(Ti)- Ione Fm.: White to red quartz sandstone, claystone, siltstone, minor conglomerate, shale and lignite.

(Gr)- Upper Jurassic quartz diorite to diorite with lesser amounts of granite to gabbro-diorite.

(Jmo)- Monte De Oro Fm.: Variably metamorphosed interbedded thin bedded graywacke, sheared siltsone, conglomerate, shale and lignite.

(Joc/db)- Slightly metamorphosed basic to intermediate pyroclastics, flows, interbedded volcanic sandstone and conglomerate: Joc - Oregon City Fm. of Creely (1965); db - "diabase" of Turner (1895).

(ams)- "Amphibolite Schist" (Amphibole-albite-epidote (-chlorite) schist): metamorphosed basic volcanic rocks.

LEGEND

(See page (37) for expanded description)

Cenozoic	Quaternary	Holocene	Qal	Alluvium (Recent)
		Pleistocene	Qt-1	40' Terrace gravels
			Qt-2	100' Terrace gravels
			Qt-3	140' Terrace gravels
	Tertiary	Pliocene	Tc Tw	Tertiary conglomerates with interbedded rhyolitic tuff
		Miocene	Tvl	Lovejoy Basalt (flows)
			Tvm	Mehrten Formation
		Eocene	Ti	Ione Formation
Mesozoic		Jurasic	Gr	granitic rocks
			Jmo	Monte De Oro Formation
			Joc db	Oregon City Formation and undifferentiated "diabase"
Paleozoic(?)		Pre-Jurasic	ams	"Amphibolite schist"

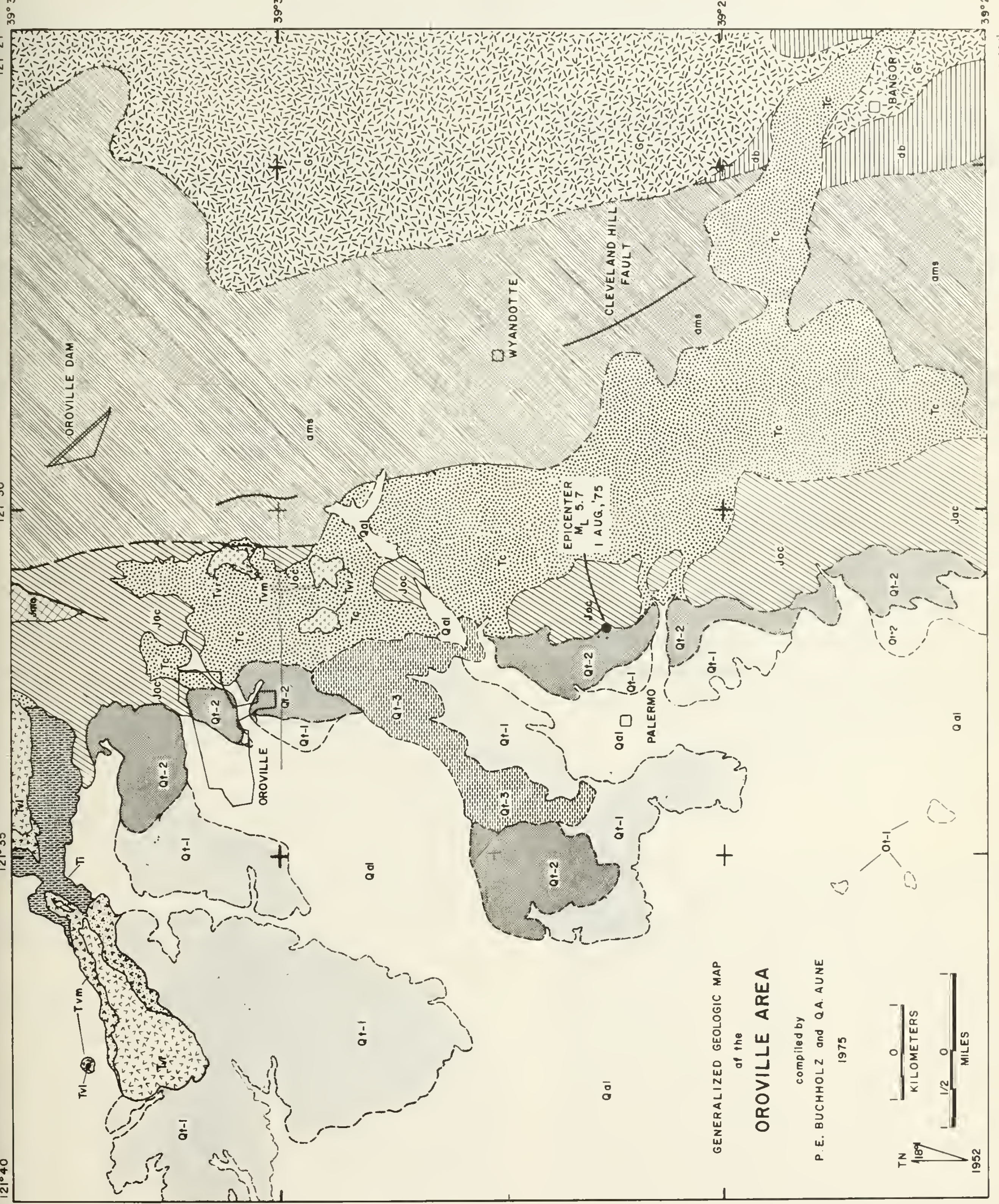

Fig. 1: Generalized geologic map of the Oroville area (modified from Lindgren and Turner (1895), Turner and Lindgren(1895), Turner(1898), Lindgren(1911), Creely(1965)).

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GEOMORPHIC SETTING OF THE CLEVELAND HILL FAULT, SOUTHERN BUTTE COUNTY, CALIFORNIA

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INTRODUCTION

Geomorphology is the branch of geologic science that deals with the classification, description, nature, origin, and development of present landforms. Allen (1975, p. 1056) has emphasized the special need for geomorphologic studies in regions of seismic risk. Such studies can serve as a rapid and powerful tool for evaluating the seismicity of an area back through Quaternary time. Thus used, geomorphology provides an effective extension to historic time in evaluating seismic risk. The following presentation is made with that goal in mind.

GEOMORPHIC FORMS, CLEVELAND HILL AREA

The Cleveland Hill area may be defined in terms of two geomorphic units or surfaces, one to the west that we shall call the Wyandotte surface, for typical exposures west of the community of Wyandotte; and one including Cleveland Hill and extending about two kilometers to the east that we shall call the Bangor surface, for typical exposures near the community of Bangor. These surfaces are shown in plan view in Figure 1, and in east-west cross-section in Figure 2. These geomorphic surfaces are separated by a west-sloping ramp-like topography, with the Wyandotte surface generally 100 to 200 feet below the Bangor surface.

The Wyandotte Surface

As seen in Figure 2, the Wyandotte surface is a slightly west-sloping geomorphic surface cut on bedrock of greenstone on the west, amphibole schist on the east, and highly dissected late Cenozoic gravel deposits generally in the central portion. The surface was formed by the ancestral Feather River as a result of erosional and depositional processes. Channels were cut around resistant nobs and hills of greenstone and lapped up against resistant masses of amphibole schist and amphibolite. There followed a period of aggrading and buildup of alluvial fan gravels, probably during Pliocene and early Pleistocene time. During subsequent lowering of base level and extensive erosion, these gravels were highly dissected, resulting in the present day surface.

The summits of the hilltops in the area of dissected gravels form a fairly even profile in a north-south direction and are probably near the elevation of the relatively undeformed original alluvial fan surface. Soils on these gravels are classed as a variant of the same soil series (Newville) formed on Plio-Pleistocene alluvial fan gravels of ancestral tributary streams on the west side of the Sacramento Valley at this latitude (Smith and Mallory, 1974, in press). The Plio-Pleistocene age of these gravels is thus based on similarities with degree of dissection, deformational history, and soil profile development of dated Plio-Pleistocene alluvial fan gravels to the west in the Sacramento Valley.

The Bangor Surface

Compared to the Wyandotte geomorphic surface, the Bangor surfac is slightly elevated, generally slightly east-dipping, and moderately undulating in form. It is generally cut on bedrock composed of amphibolite or amphibole schist, but in the vicinity of Bangor, granitic rock types and erosional remnants of Plio-Pleistocene stream channel deposits are locally present. The east boundary of the Bangor surface is provisionally placed at a break in slope in part coincident with the contact of the schist and amphibolite on the west with dioritic, gabbroic, and granitic rocks that underlie the more mountainous terrain to the east. The change in topographic form may be due to differences in rock fabric and structure, rather than to faulting or surface age differences. There appears to be little or no oversteepening of stream gradients of the two major streams, North Honcut Creek and Rocky Honcut Creek, that drain this more rugged granitic terrain.

In contrast, the gradients of these two streams, as well as that of Wilson Creek, west of Bangor, show local oversteepening as they approach and cross the slope separating the Bangor surface on the east from the lower Wyandotte surface to the west. Based on soils map unit boundaries and preliminary geologic reconnaissance, the Plio-Pleistocene channel - probably of ancestral Honcut Creek - represented by the stream channel gravels, also oversteepens significantly as it crosses the Wyandotte-Bangor geomorphic boundary area four kilometers northwest of Bangor.

This evidence, coupled with general anomalous eastward-slope of the Bangor surface in contrast with the generally west-sloping Sierra Foothill front, suggest Quaternary structural deformation may be the primary agent responsible for much of the present geomorphic form of the Bangor surface and its western boundary. The similarity of composition and texture of rock type - amphibole schist and amphibolite - across the boundary between this surface and the Wyandotte surface to the west also tends to support this conclusion.

GEOMORPHIC RELATIONS OF THE CLEVELAND HILL FAULT TREND

The Cleveland Hill fault lies along a north-northwest trend marking an irregular break in slope along the Sierra Nevada foothills in southern Butte County and possibly extending south into Yuba County. (Figure 3). This break in slope marks the approximate line of eastward termination of most Late Cenozoic outcrops. The break in elevation is in the form of a somewhat discontinuous west-facing topographic "ramp", with about 300 feet of differential elevation in the vicinity of Swain Hill, north of Loma Rica; 350 feet of differential elevation southwest of Katskill Hill, near Bangor; 150 feet of differential elevation west of Cleveland Hill, near Wyandotte; and at least 300 feet of differential elevation west of Kelley Ridge, overlooking Lake Oroville and Oroville Dam. In the plan view, the ramp is somewhat herringbone-like in trend (Figure 3).

The area west of this west-facing topographic "ramp" coincides with the Wyandotte geomorphic surface described above; the area to the east coincides with the Bangor surface.

The Cleveland Hill fault lies generally along the base of the "ramp" in the vicinity of Cleveland Hill. Topography related to the fault is sufficiently subdued that this feature probably would have been recognized as a geologic fault only with difficulty, and then only on the basis of careful, detailed geologic mapping, prior to formation of the rupture zone along the fault coincident with the August 1, 1975, Oroville earthquake. Considering field criteria described by Wallace (1975) and allowing for climatic and erosional rate differences between Wallace's northern Nevada map area and the Cleveland Hill map area, one would still be inclined to conclude that the geomorphic forms in the vicinity of the Cleveland Hill fault would indicate a very low level of seismicity there, with earthquakes of perhaps no stronger than 6 magnitude occurring only once every two or three thousand years or so on any one segment of the fault.

Thus, a critical question becomes: How long is the Cleveland Hill fault? Did rupturing which occurred during the August 1, 1975, Oroville earthquake take place along much of the total length of the fault Or did this rupture occur only along a very local segment of the fault where stres reached the critical point, resulting in an earthquake? Did extensions of the fault to the south and/or to the north fail to rupture because stress had not yet reached the critical point along fault segments in these areas?

As we have seen above, the Cleveland Hill fault coincides roughly with the base of the slope bounding the Wyandotte geo-

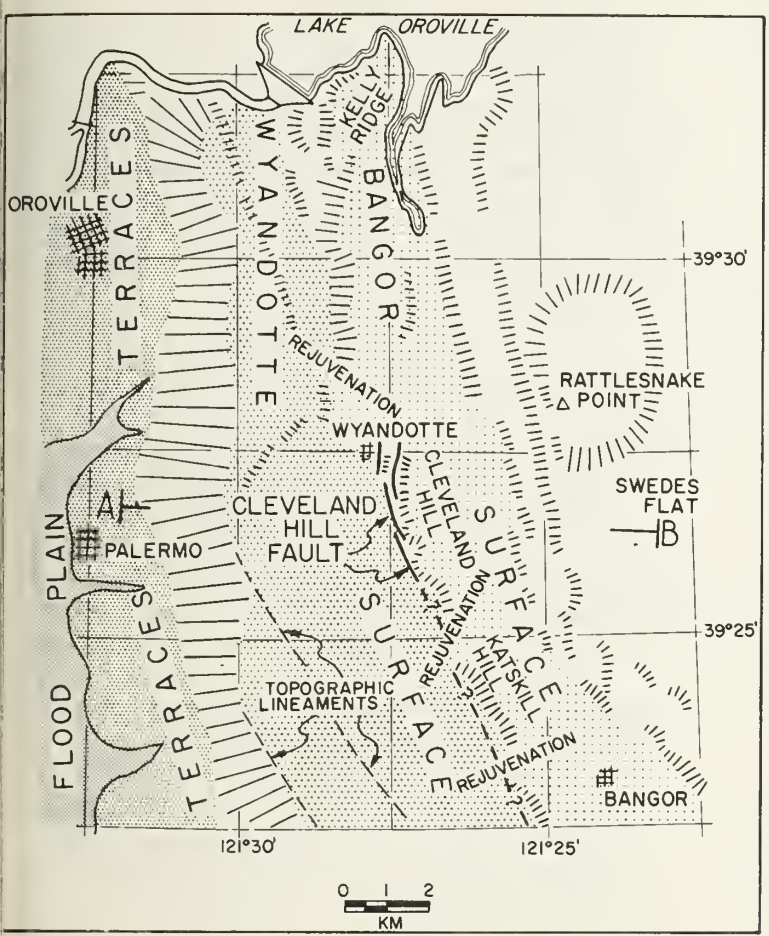

Figure 1. Geomorphic surfaces, Cleveland Hill area, Butte County. "A", "B" indicate end points of cross-section, Figure 2.

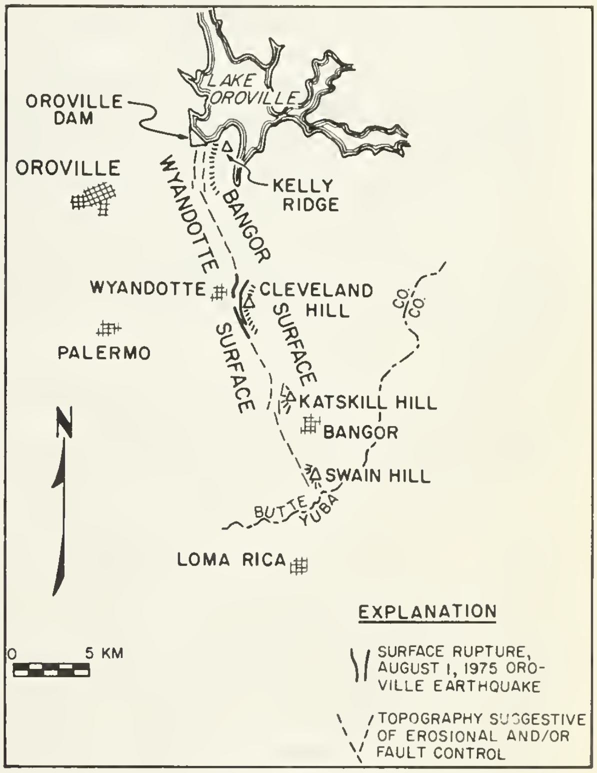

Figure 3. Relation of zone of fracture along Cleveland Hill fault to irregular lineament forming boundary between Wyandotte and Bangor geomorphic surfaces.

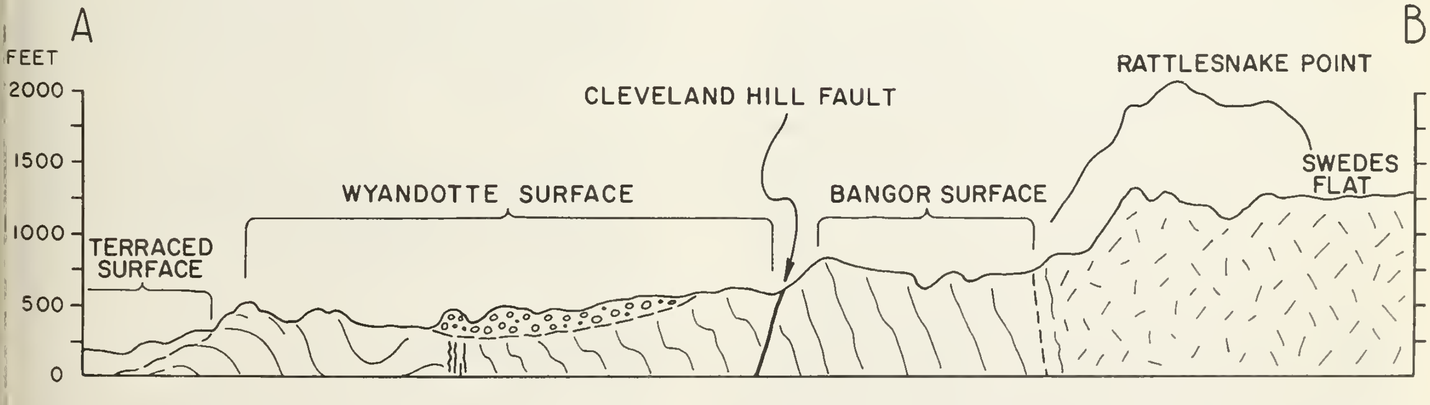

Figure 2: Cross-section view of the Wyandotte and Bangor geomorphic surfaces and the dissected mountain front to the east. View facing north, in vicinity of Cleveland Hill fault. Cross-section end points "A". "B" are shown on map, Figure 1.

morphic surface on the west and the Bangor geomorphic surface on the east. South of the fault, where present day streams cross this geomorphic slope between Cleveland Hill and Bangor, the gradients of these streams are oversteepened, suggesting a possible structural control of the slope, caused by faulting. Oversteepening of the gradient of an ancient stream as represented by the anomalous distribution of dissected Late Cenozoic stream channel deposits also suggests active structural control. Normal faulting such as that occurring during the August 1, 1975 earthquake on the Cleveland Hill fault would provide such control.

North of Cleveland Hill, geomorphic evidence is unclear. As a geomorphic force, the present day Feather River, where its canyon crosses from the Bangor to the Wyandotte surface has far too much erosive energy to submit to oversteepening as a result of the apparently modest rate of fault movement along the Cleveland Hill trend. Other drainages crossing this geomorphic boundary in this area are too poorly developed to be definitive, although the head of a branch of Wyman Ravine, one kilometer north of Wyandotte, does show some semblance of rejuvenation on the geomorphic boundary area. However, lacking modern geologic mapping in this area, it is impossible to tell what part other factors, such as differential resistance to erosion, might play in providing an appearance of stream rejuvenation.

CONCLUSIONS

The August 1, 1975 Oroville earthquake produced surface ruptures along the base of irregular, subdued and erosion-modified scarps that form the west flank of Cleveland Hill. These scarps also form the boundary between two geomorphic surfaces, the gently westward dipping Wyandotte surface to the west, and to the east, the Bangor surface, an undulating surface dipping somewhat to the east. Between Cleveland Hill and Bangor to the southeast, oversteepening of stream gradients and a Late Cenozoic channel course, where these features cross the west-facing slope between the two surfaces are locally oversteepened, suggesting possible structural control (faulting) for th slope between the surfaces. North of Clev land Hill, geomorphic relations are inconclusive. Detailed geologic studies will b necessary to determine the causes for the slope between the low-lying Wandotte surfa west of Kelly Ridge, and Kelly Ridge, the southern portion of which forms the high western margin of the Bangor surface in that area.

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ACKNOWLEDGEMENTS

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GEOLOGIC INVESTIGATION OF THE OROVILLE EARTHQUAKE

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ABSTRACT

The California Department of Water Resources has begun geologic studies to determine how the occurrence of the Oroville earthquake affects their evaluation of the seismic hazard to Oroville Dam and related facilities. Objectives of the study are to identify and explore any faults on which movement related to the recent earthquake has produced ground surface rupture, and to relate such faults to the local geology and the regional tectonic framework. Methods being used include study of various types of aerial imagery to identify lineaments which may be faults, geologic field mapping of the epicentral and project area with special attention given to suspect lineaments, and subsurface exploration to confirm fault locations. Several crack zones, one now known to occur along a fault, were located and are described.

INTRODUCTION

The August 1, 1975, magnitude 5.7 earthquake near Oroville, California, was of particular concern to the California Department of Water Resources because of its proximity to the Department's Oroville Dam and related facilities. The epicenter of the main shock was about 11 km southwest of Oroville Dam and even closer to some of the downstream facilities (Figure 1).

Post earthquake inspection revealed no significant earthquake related damage to project facilities. However, the occurrence of the earthquake in an area where no faults were previously known and which was generally considered to be seismically relatively quiet, has posed several geologic questions. First, did fault movement break the ground surface, and if so, would renewed slippage endanger project facilities? Second, how would these fault movements fit into the regional tectonic framework? And third, what is the potential for future seismic activity?

Investigations designed to answer these questions, at least in part, are currently underway. This paper is in the nature of a progress report: a brief description of the ongoing investigations and the several geologic features, known to be related to the earthquake, which are currently being examined.

GEOLOGIC SETTING

The Oroville area lies astride the western margin of the Sierra Nevada. Rocks of this area have been divided into two distinctive groups designated the "Bedrock Series" and the "Superjacent Series" (Creely, 1965)(Figure 1).

In the central portion of the area the foothills are underlain by metamorphosed Paleozoic and Mesozoic sedimentary and igneous rocks intruded to the east by granitic plutons. The metamorphic rocks, which together with the granitic rocks comprise the Bedrock Series, have been severely folded and exhibit a north-south trending system of steeply dipping bedding, joints, foliation, and shears. In the western portion of the area, extending into the Sacramento Valley, gently dipping to flat-lying sedimentary and volcanic rocks rest unconformably on the rocks of the Bedrock Series. These rocks, which range in age from Cretaceous to Recent, comprise the Superjacent Series.

The northern extension of the Foothill fault system is the main tectonic feature of the Oroville area. This fault system extends for about 300 km along the western edge of the Sierra Nevada; from east of Merced in the south to about 50 km north

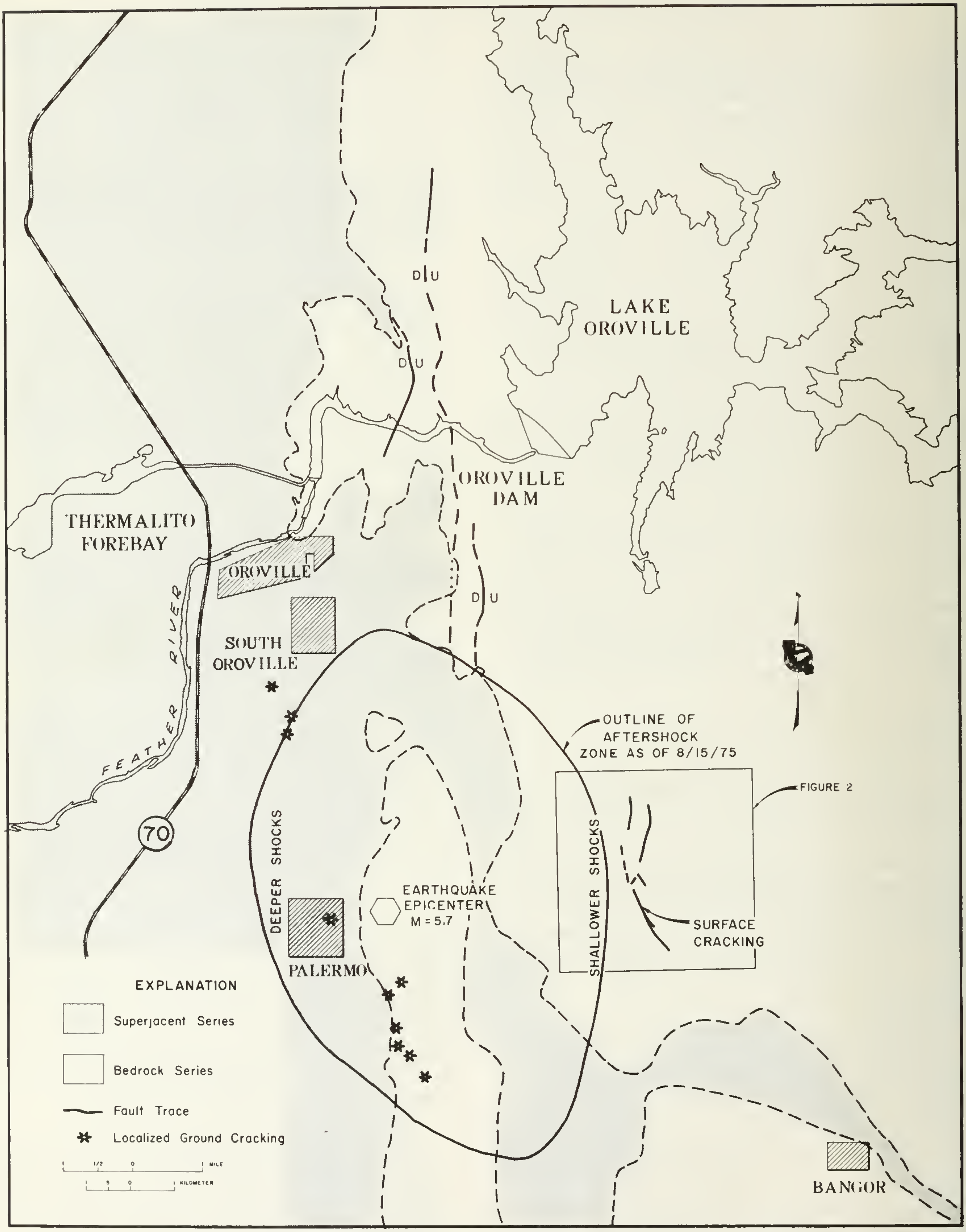


Figure 1. Generalized geology and locations of ground cracking.

of Oroville. The southern portion of the Foothill fault system consists of the Melones fault zone to the east and the Bear Mountain fault zone to the west. As the fault system is traced northward the two fault zones spread apart with the Melones fault zone passing about 25 km to the east of Oroville and the Bear Mountain fault zone no longer traceable about 20 km south of Oroville. The Foothill fault system is thought to be of late Jurassic age, and has, for many years, been presumed to be inactive.

Several other smaller faults have been mapped in the area and there are probably still others which have not been detected because of poor exposures and rugged brushy terrain.

GEOLOGIC INVESTIGATIONS

Field Reconnaissance

Shortly after the August 1, 1975 shock, field reconnaissance was begun in an attempt to locate ground ruptures or cracks which might be indicative of fault movement. Numerous locations of ground cracking which had been reported by residents were inspected and evaluated. The most significant cracking discovered was in a zone along the western flank of Cleveland Hill, about 8 km east of Palermo (Figure 1).

Field inspections were also made of three known faults previously mapped in the vicinity (Figure 1). These faults trend in a northerly direction and two of them extend across the Feather River 2 to 3 km west of Oroville Dam. No evidence of recent movement was discovered along any of these faults. Several seeps and springs near the surface traces of two of these faults were reported to have increased in flow shortly after the August 1 shock, but many springs not in the vicinity of known faults were also reported to have been similarly affected.

Lineament Studies

Several types of aerial imagery of the epicentral and project area were obtained and are being used to detect lineaments that may represent faults. These include side-looking-airborne-radar (SLAR), ERTS/LANDSAT imagery, and U-2 color infrared photography. In addition, both high-sun-angle and low-sun-angle aerial photography at a scale of 1:12,000 were obtained for use in the lineament studies and as a base for field mapping.

Lineaments identified as potential fault traces are being examined in the field. Selected lineaments and cracks are being explored by trenching to determine if they are faults. To date, four trenches have been excavated across the Cleveland Hill crack zone.

SURFACE OBSERVATIONS

Cleveland Hill Crack Zone

On August 6, 1975, a linear crack zone was discovered along the western flank of Cleveland Hill, about 8 km east of Palermo (Figure 2). The zone is about 1,600 m long and has a short branch beginning near the midpoint and extending about 200 m in a southeast direction. The crack zone varies from about 1 m wide to a maximum of about 7 m wide, and consists of a series of individual en echelon cracks. The zone trends from 15° to 35° west of north and the individual cracks have an average trend ranging from 5° to 15° west of north. Looking forward along the zone, the en echelon cracks are offset to the left of one another, indicating a component of the zone displacement to be right-lateral strike slip. The cracks are fairly continuous, although often not traceable across marshy ground.

In late August and early September the entire crack zone was mapped at a scale of 1:120 (1 inch equals 10 feet). At that time the maximum width of individual crack openings was about 40 mm and the maximum measured depth was about 0.6 m. Most of the cracks exhibited little or no vertical displacement; however, a maximum of about 30 mm was noted at two locations, with the west side being

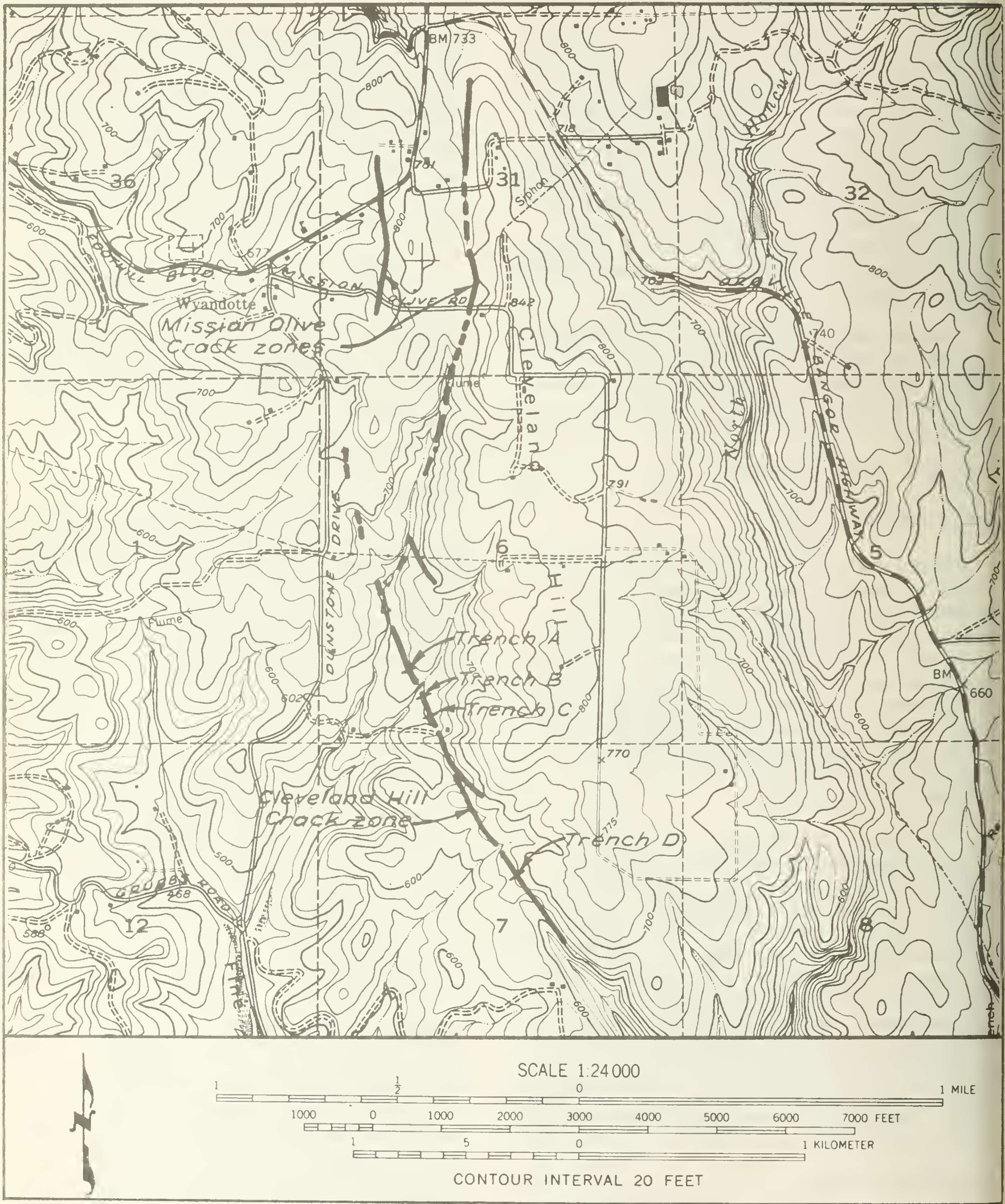


Figure 2. Cleveland Hill and Mission Olive crack zones and exploration trench locations.

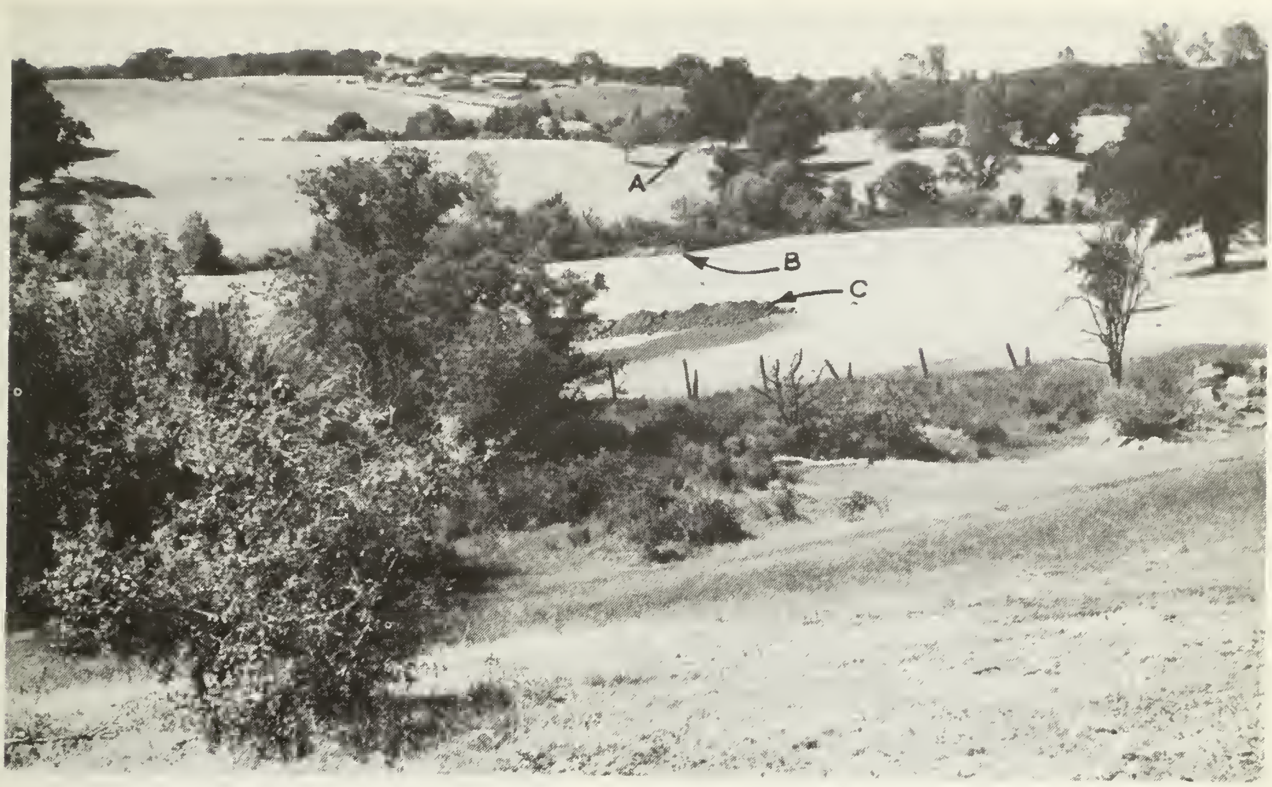


Figure 3. View looking northwest along portion of Cleveland Hill crack zone, showing locations of exploration trenches A, B, and C.

displaced downward relative to the east side. Repeated inspections have shown individual cracks have continued to open and the zone has continued to lengthen since first observed on August 6th. Also, the same sense of movement has continued on individual cracks so that by the middle of October, some amount of vertical displacement was obvious along nearly the entire crack zone.

Surface evidence suggests that the crack zone follows a fault. At several locations near the middle of the zone, underflowing runoff of irrigation water from Cleveland Hill rises to the ground surface along the alignment to form enlarged expanses of phreatic grass. A linear valley, two springs, and contrasts in vegetation mark southern extensions of the zone. Topographic configuration of the crack zone suggests the fault would be vertical or very steeply inclined to the west near the ground surface.

Mission Olive Crack Zones

Early in October, two crack zones were discovered north of the Cleveland Hill crack zone (Figure 2). These two zones are roughly parallel, about 400 m apart, and trend about due north. These zones are similar in nature to the Cleveland Hill crack zone but are not as continuous. They were followed intermittently for about 2 km to the north. Both zones have broken the asphalt pavement where they cross Mission Olive Road, and the westerly zone has also broken the asphalt pavement on Foothill Boulevard farther to the north.

Palermo Crack Zone

Among the many ground cracks mapped in the unconsolidated sediments and man-made fills around Palermo and South Oroville are some whose locations appear anomalously aligned and coincident with a lineament

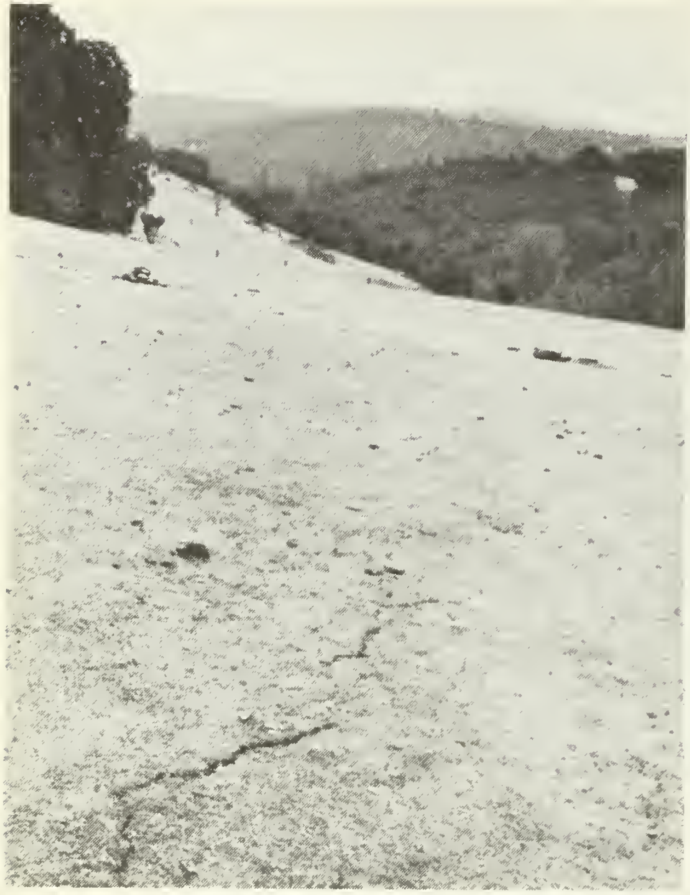


Figure 4. View looking southeast along southernmost portion of Cleveland Hill crack zone. Crack ends in marshy area on near side of wooded ravine in background.

that locally marks the western edge of the foothills. The cracks are identified as localized ground cracking on Figure 1. They range from faint cracks diagonally crossing roadways, to distinctive singular ones extending several tens of meters, to small areas of strongly shattered ground with individual cracks open to 75 mm wide. Several buildings were damaged along the alignment. One, a modern frame residence, was the most extensively damaged building in the epicentral area.

Although the crack locations are aligned, the orientations of individual cracks are not. Crack orientations appear more related to topography than lineament direction.

TRENCH OBSERVATIONS

On August 20 and 21, 1975, four exploration trenches were excavated across the Cleveland Hill crack zone (Figure 2). The trenches were excavated down to moderately hard metavolcanic bedrock or to a maximum depth of about 2 m in softer materials.

Three of the trenches (Figure 6) exposed an old steeply dipping fault zone cutting metavolcanic bedrock. The zone contains from 2 to 3 m of plastic gouge and up to 1.5 m of breccia. The fault and adjacent weathered bedrock are overlain by 0.3 to 0.6 m of reddish-brown residual soil. Generally the bedrock is strongly weathered to decomposed at the soil contact, with the degree of weathering decreasing rapidly with increasing depth. Boundaries of the various units logged in the exploration

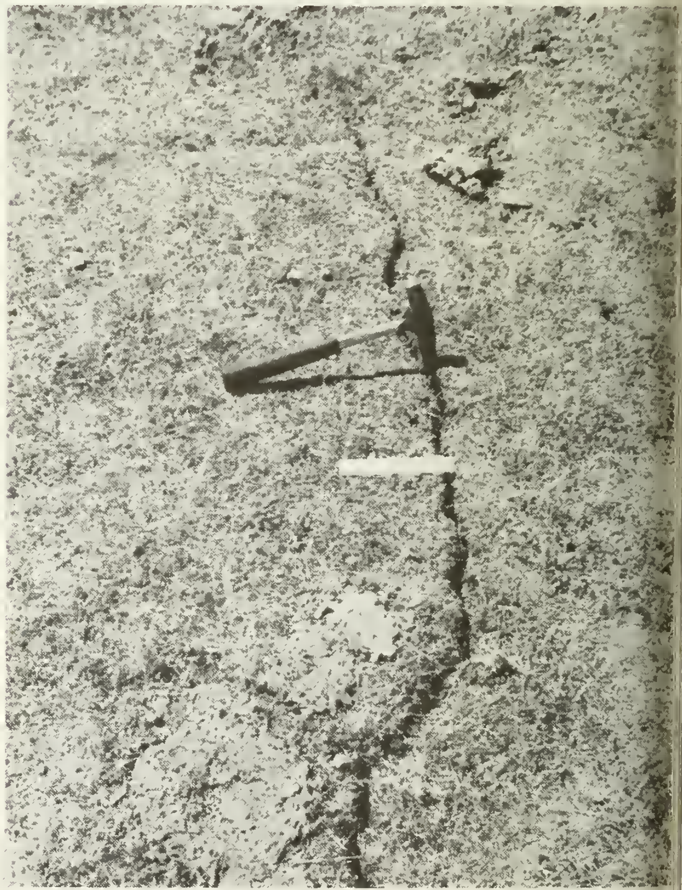
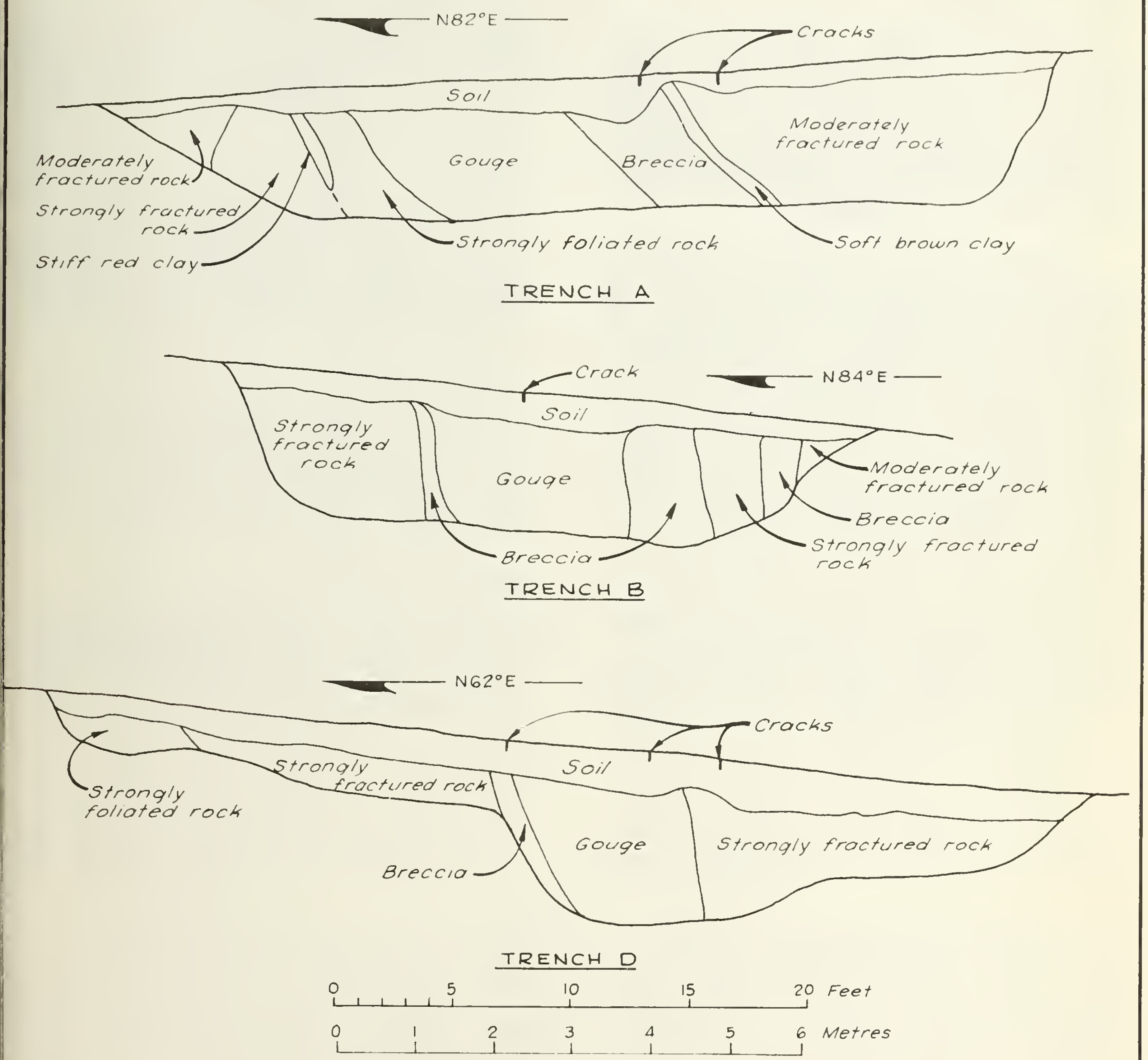


Figure 5. Closeup view of portion of crack shown in foreground of Figure 4. Crack open about 20 mm, west (right) side down about 25 mm.



Rock: Metavolcanic, dark gray to greenish-gray, massive to strongly foliated, moderately to strongly fractured, fracture surfaces commonly limonite stained, grades from strongly weathered near soil contact to moderately weathered at depth.

Breccia: Crushed fragments of metavolcanic rock, generally with some clay matrix.

Gouge: Plastic clay, grades from reddish-brown near soil contact to greenish-gray at depth.

Soil: Silty, reddish-brown, friable, residual soil.

Figure 6. Logs of exploration trenches across Cleveland Hill crack zone.

trenches are generally irregular, gradational, or both.

The fourth trench (Trench C) was excavated in an area of deep soil and colluvium in which the fault zone boundaries were obscure. Because of this, and a hazardous sloughing condition of the trench walls, detailed inspection and logging of this trench were not attempted.

Although the cracks could be seen penetrating the soil layer, they could not be traced into the underlying materials. No vertical displacement of the bedrock surface was evident in the three logged trenches. The limited extent of the soil-bedrock contact exposed in the trenches and the natural irregularity of the bedrock surface, however, would tend to mask vertical displacements of the small magnitude observed at ground surface.

SUMMARY

The Cleveland Hill crack zone appears to have resulted from movement on the northwest trending fault, probably having a steep dip to the west, which was exposed in exploration trenches. Movement on the fault appears to have been both normal, with the west side down relative to the east side, and right-lateral strike slip. This fault is probably the fault or one of the faults directly related to the Orovill earthquake sequence. The Mission Olive crack zones probably were caused by simila movement on closely related faults. Geologic investigations are proceeding on the basis of these assumptions. Determination of the tectonic significance of the Palerm crack zone will require further studies, which are contemplated for a future time.

ACKNOWLEDGEMENTS

We thank John W. Marlette and Wilferd W Peak for reviewing this paper, and Harold L. Allsup and John W. Marlette for allowing us unrestricted use of their field notes and mapping.

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OBSERVATIONS OF GROUND BREAKS IN THE OROVILLE AREA, CALIFORNIA; MADE DURING RECONNAISSANCE EXPLORATION IN AUGUST 1975

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INTRODUCTION

Seven earthquakes greater than 4.6 Richter magnitude were recorded in the Oroville area during the week of August 1 through August 8, 1975. The area from Oroville Dam south to Honcut and Bangor was traversed by vehicle and on foot to discover and document earthquake-related ground breakage and damage to man-made structures (figure 1). Most of the observations listed in this paper were fractures reported to the Division of Mines and Geology by the public. Field checks were made to document the reported breaks.

Soils of the Oroville area are generally clay-rich and expansive. These soils desiccate and crack during the summer months and become quite coherent and brittle. Consequently, many of the cracks seen in the field were simply caused by desiccation of soils and were not related to seismic shaking or fault displacement. In other cases the observed ground breaks crossed roads, driveways, and other man-made structures that normally would not be subject to desiccation cracks.

This paper describes ground breaks related to seismic shaking and, in some cases, possible minor fault displacement. Ground breaks that formed during the August earthquakes formed for several reasons; lurching, differenetial compaction, slumping towards a free face, internal stresses caused from the dehydration of soils, and other phenomena. Regardless of the mechanism by which the breaks formed, they were all induced by seismic shaking or possible fault displacements. Most of the ground breaks are listed in Table 1. Observed ground breaks and features that may indicate fault displacement are briefly discussed in the text. All items are numbered and located in figure 1, the index map. The Cleveland Hill fault is described in at least one other paper of this report (see Hart and Rapp).

GROUND BREAKS AND OTHER FEATURES WHICH MAY INDICATE MINOR FAULT DISPLACEMENT

North Honcut Creek Area

A zone of cracks approximately 600 meters long skirts the hillside along the northwest bank of North Honcut Creek at location (1a) in figure 1. The zone trends about N55°E and is not restricted to a single narrow zone. The cracks are open and irregular. Another zone of cracks, similar to the breaks along North Honcut Creek, was observed at location (1b) about 1 kilometer along strike to the southwest. At location (1c) three hundred meters along strike to the northeast of location (1a) a narrow zone of ground breaks cross a dirt road. These breaks strike about N15°E across the road and from an incipient right-stepping en echelon pattern (photograph 1). Still further to the northeast along strike (N55°E) 3 right-stepping (?) en echelon breaks cross Fine Gold Gulch Road at location (1d). The largest crack is approximately 15 meters long and has a maximum horizontal separation of about 2 centimeters.

A barbed wire fence at location (1b) trends due north from Cox Lane and is bowed approximately 1 meter to the west (photograph 2). The bowed fence, which is located on a gently sloping hillside used for cattle grazing, may have been displaced by downslope soil movement. There appears to be a higher percentage of clay in the soil of this area.

A lineament can be observed in high altitude SLAR and conventional photographs. The linear topographic expression of this North Honcut Creek lineament suggests the existence of a vertical or steeply dipping joint system or fault zone.

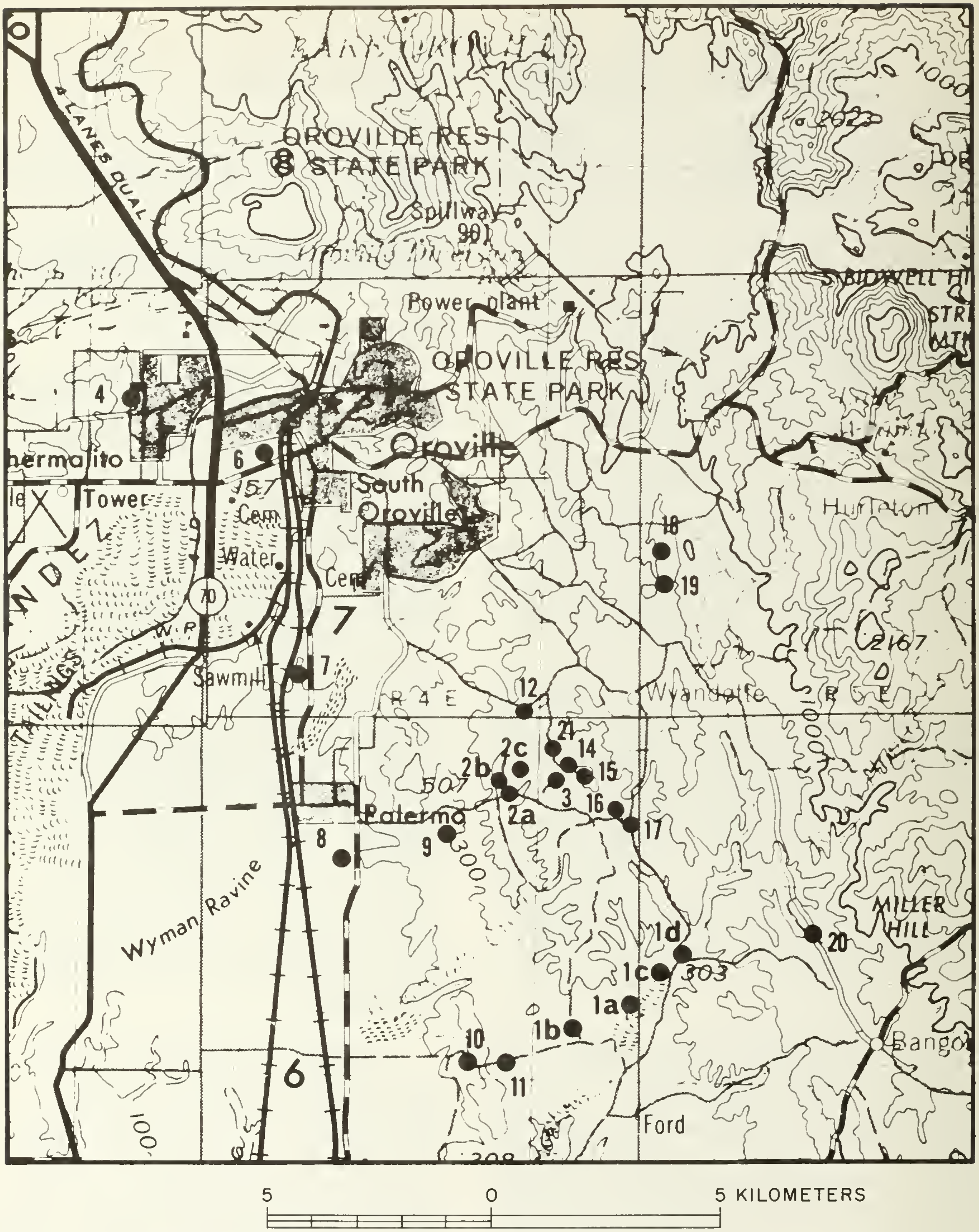
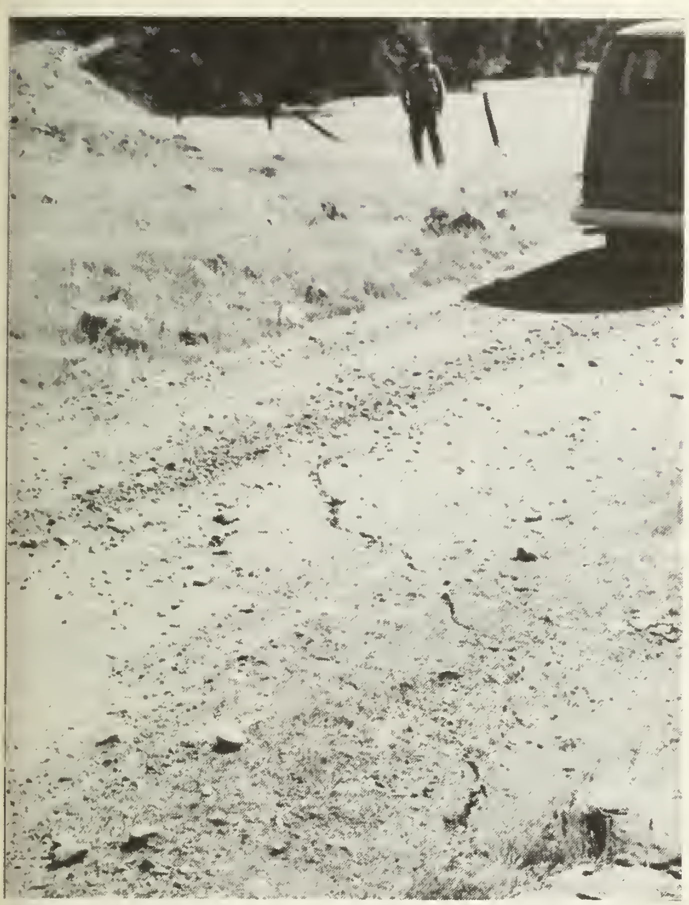


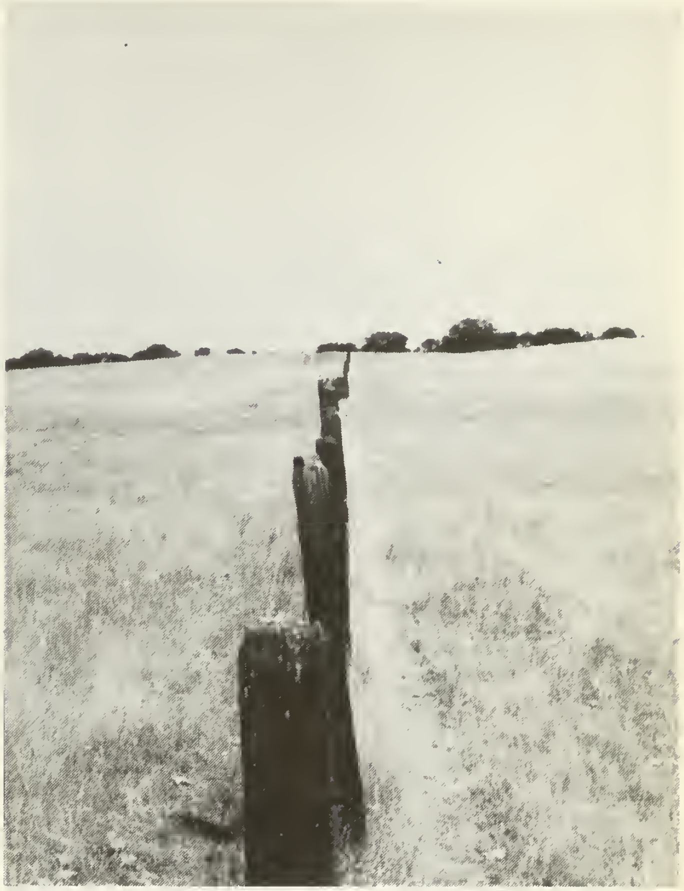
Figure 1. Index map of the Oroville area showing the location of ground breaks. Numbers shown above refer to descriptions in the text.

Summit Avenue Area

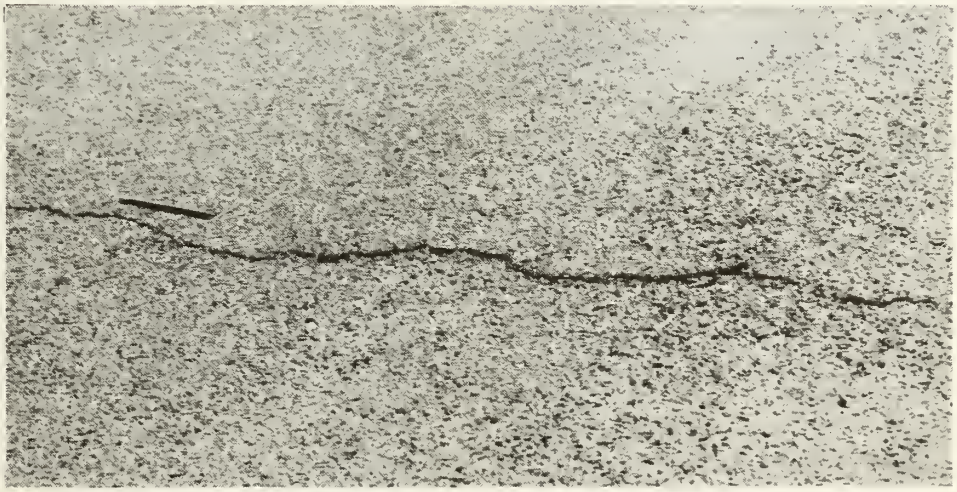
Summit Avenue is located at the crest of a ridge that trends about N30°E for approximately 1.5 kilometers. The south end of the ridge meets Grubbs Road at location (2a) where Wyandotte Creek crosses Grubbs Road. The north end of Summit Avenue intersects District Center Road at the othe end of the ridge.



Photograph 1. Incipient right-stepping ground breaks across dirt road at North Honcut Creek, viewing southwest.



Photograph 2. Bowed fence that crosses the North Honcut Creek lineament near Cox Lane. The view is due North.



Photograph 3. Ground break across Grubbs Road near Wyandotte Creek. Three fractures crossed the road at the base of Summit Avenue ridge. Others were found at culverts that crossed Grubbs Road at Wyandotte Creek.

Photograph 4. Bent corral fence on Summit Avenue ridge, viewing south. The northeast corner of the corral appears to be displaced approximately 25 cm to the west. The southwest corner of the corral is damaged and leaning to the north.

Two N50°E trending ground breaks and a N35°E ground break crossed Grubbs Road at location (2a) (photograph 3). Two concrete culverts within 150 meters of these cracks separated from the asphaltic pavement of Grubbs Road by a few millimeters. The Butte County road department resurfaced Grubbs Road before closer measurements could be made. A discontinuous zone of fractures, ranging in length from a few centimeters to several meters, was observed on the ridge from Grubbs Road to a place on Summit Avenue about 500 meters to the northeast. The fractures were largely restricted to the surface of a dirt road extension of Summit Avenue that follows the ridge crest. Maximum horizontal separation was less than a centimeter.

A few hundred meters northeast of the ground breaks along the ridge, at location (2b), an old corral may have been damaged by seismic shaking or fault displacement. The northeast corner of the corral appears to be bent to the west by about 25 centimeters (photograph 4). The southwest corner of the corral is damaged and leans to the north. No ground breaks were observed in the vicinity of the corral, but a wooden frame house on the property suffered fairly heavy damage as did other houses on Summit Avenue.

Mr. A. W. DeCamp has two water wells on his property which is located on the southwest flank of Summit Avenue ridge at location (2c). The bed of Wyandotte Creek, which was dry during August, is located approximately 15 meters west of DeCamp's wells and about 4 meters below the well heads. One well was hand dug to a depth of about 5 meters and the other well drilled to about 24 meters. According to Mr. DeCamp, the original water level was approximately 4 meters below ground level. Several years ago a small dam was built upstream, at the head of Wyandotte Creek in Wyandotte, and the level in DeCamp's wells dropped about 2 meters. Since then the water level has remained about 6 meters below ground level in the drilled well. After the August 1 earthquake both wells became free flowing for 2 days. Then the water level subsided in both wells about 60 centimeters and was observed at that level throughout August.

Woodland Lane Area

Woodland Lane is a narrow dirt road located about 1 kilometer east of Summit Avenue at location (3). Three left-stepping (?) en echelon cracks crossed the road near the crest of the hill and continued for a few meters into the shoulder of the road. The trend of these ground breaks was about N90°E with the longest break being 12 meters long and two other breaks being 5 meters each (figure 2). Maximum horizontal separation was approximately 2 centimeters. Many other ground breaks were found in the area, but these were related to differential compaction of fill materials and lurching.

Thermalito Area

Cracks were observed in a grassy area on the south side of Butte Avenue in Thermalito (location 4). The individual breaks were less than 3 meters in length, and had a maximum of 7 centimeters of horizontal separation. There was no systematic pattern to the distribution of the cracks.

A barbed wire fence runs along the south side of Butte Avenue for several hundred meters. The entire fence, with the exception of a 60 meter section, was constructed with split wooden posts and strands of tight barbed wire. The fence is well made and appears to be several decades old (figure 3).

A few hundred meters west of the intersection of Butte Avenue and 12th Street, a portion of the older fence has been replaced by a new fence constructed of steel fence posts and barbed wire. The new fence connects separated sections of the older fence. The strike of the older sections of fence is N90°E, and the strike of the new fence is N88°E. It appears that the old fence has been offset left-laterally about 2 meters. The cracks reported by the Thermalito resident are located near the east end of the new dection of fence (figure 3). Ground breaks were not found in the pasture just south of the fence or on Butte Avenue. Furthermore, there were no recent cracks on Tehama Avenue which is the nearest east-west running street south of Butte Avenue.

A gentle valley with a south flowing creek lies west of the offset (?) fence at Butte Avenue. The area east of the offset (?) fence is higher in elevation than the area to the west. The change in elevation is probably due to the termination of a Pleistocene (?) alluvial terrace that underlies much of the area to the east. If the old fence is not simply the result of poor surveying or construction, then the offset must have developed gradually. No fault scarps or breaks were observed in the area other than the randomly oriented fractures reported by the local resident.

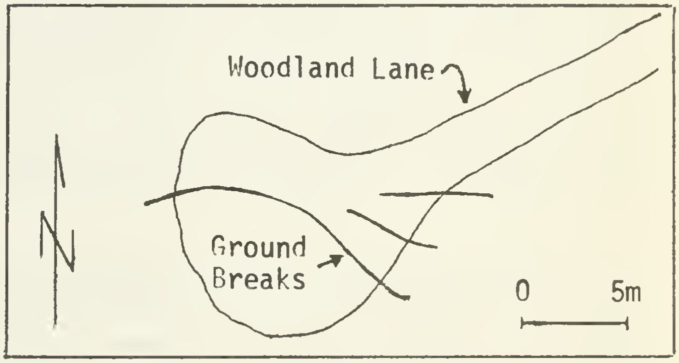


Figure 2. Sketch map of Woodland Lane

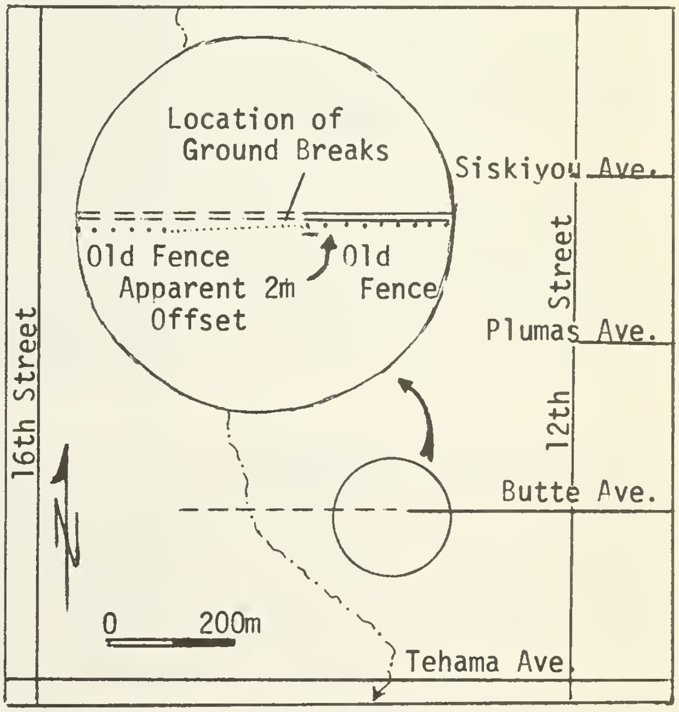


Figure 3. Sketch map of Thermalito Area

TABLE I

Minor Ground Breaks in the Oroville Area Caused by Ground shaking.

	Latitude	Longitude	General Description
** 5)	39°25.5'	121°36.5'	A zone of cracks approximately 700 meters long formed along the levee road just west of Oak Grove. Most of the cracks formed longitudinally and followed the levee road. Similar cracks formed along levees 3 kilometers to the north along the Feather River near Oroville. Horizontal separation generally varied from a few millimeters to a centimeter.
6)	39°30.4'	121°33.5'	A 30 meter long crack, trending N80°E, was found in an area adjacent to a baseball diamond in south Oroville.
7)	39°27.5'	121°33.2'	A zone of cracks approximately 30 meters long formed on Custer Avenue in Palermo. The longest crack was 7 meters and maximum separation was 5 millimeters. Custer Avenue runs north-south.
8)	39°25.4'	121°32.5'	Several ground breaks formed in the earthen dam and embankments of a stock pond near Palermo.
9)	39°25.7'	121°30.9'	An east trending ground break formed across a rural dirt road and continued for approximately 1 meter into a grassy area. Maximum observed horizontal separation was approximately 10 centimeters.
10)	39°23.2'	121°30.5'	Numerous open cracks were found along Cox Lane east of Palermo for about 300 meters. Long breaks formed parallel with the road and shorter cracks crossed perpendicular to the road. Cracks may be related to moisture in the soil.
11)	39°23.1'	121°30.1'	Numerous open cracks crossed Cox Lane, some with an apparent trend of N70°E. Maximum horizontal separation was 10 centimeters. Cracks may be related to moisture in the soil.
12)	39°27.3'	121°28.8'	North-south trending cracks crossed a driveway near Wyandotte, and each was approximately 4 meters long. A small earthen dam located about 150 meters away was cracked in several places from differential compaction of the earthfill.
13)	39°25.0'	121°29.5'	A zone of cracks was observed along the west side of Wyandotte Creek and on the gentle slope to the west. The zone was approximately 200 meters long and about 80 meters wide The cracks were largely restricted to the lowlying river bottom area. Maximum horizontal separation of these cracks, which lacked polygonal or systematic distribution, was approximately 10 centimeters.
14)	39°26.7'	121°29.1'	An east-west crack formed in concrete pad of a garage on District Center Road. The crack was at least 3 meters long.

** Items 1 through 4 described in the text.

TABLE I (continued)

	Latitude	Longitude	General Description
15)	39°26.7'	121°28.8'	Several northeast tending cracks formed in the adobe soil adjacent to a heavily damaged wooden house near District Center Road and Woodland Lane.
16)	39°26.0'	121°28.3'	Three N40°W ground breaks formed in the driveway of a ranch house near the intersection of Grubbs and Dunstone Roads. The 3 cracks were in line with one another, and the southernmost crack broke the asphaltic concrete driveway at Grubbs Road. The southern crack was 15 meters long with a maximum horizontal separation of about 5 millimeters. The next crack to the northwest was about 25 meters long and had a maximum horizontal separation of about 10 centimeters. According to the owner of the driveway, a stick over 2 meters long was dropped into the open crack after the August 1 main event, and aftershocks gradually reduced the width of the opening. The third crack was approximately 7 meters long with a maximum horizontal separation of approximately one centimeter. Both of the northern two cracks formed in unpaved portions of the driveway.
17)	39°25.9'	121°28.1'	Northeast trending cracks formed at the intersection of Dunstone and Grubbs Roads. Fine Gold Gulch was mined by dragline dredge, and these roads were placed over dredged ground. The cracks in the intersection are likely due to the differential compaction of coarse tailings and "slickens".
18)	39°29.0'	121°27.4'	Several cracks were observed in the pavement on Miners Ranch Road. Each crack was approximately 6 meters long and parallel to the north-south trending road.
19)	39°28.7'	121°27.5'	A straight 15 meter long crack was found in the back yard of a residence on Miners Ranch Road. The trend of the crack was N20°W, and maximum horizontal separation was less than a centimeter. Miners Ranch Road also trends N20°W as does geologic structure in the area. The cracks crossed an unpaved driveway and continued into a pasture and cultivated garden.
20)	39°24.6'	121°25.2'	A small earthen dam and pond exist at the base of Whitehall ravine, just west of Bangor Highway, about 3 kilometers north of Bangor. Gas began bubbling from the pond after the August 1 earthquake in two distinct lines across the pond. Each line of bubbles was about 7 meters long and oriented N20°W, which approximates the regional trend of topography and geologic structure. The bubbles were observed throughout the month of August.
21)	39°26.7'	121°29.3'	Cracks approximately 7 meters long formed in two places on District Center Road near the creek crossing. The cracks were parallel to the road and near the east shoulder.

GROUND RUPTURE ALONG THE CLEVELAND HILL FAULT

By Earl W. Hart and John S. Rapp
California Division of Mines and Geology

On August 1, 1975 an earthquake of about 5.7 magnitude shook the Oroville-Palermo area of Butte County, California. Numerous associated earthquakes also have shaken the area. Aside from damage and other secondary effects caused by the shaking, surface ground fractures were created in the area east of Palermo. Most of these fractures apparently were caused by shaking effects and are secondary (see accompanying articles by Rapp, Buchholz and Aune, and by Akers and McQuilkin). However, one set of northwest-trending fractures 6 kilometers east of Palermo are clearly related to primary faulting. This fracture zone delineates a fault not reported prior to the August 1, 1975 earthquake. The fault described herein is referred to as the Cleveland Hill fault (figure 1). The ground fractures associated with this fault were observed and mapped by the authors on August 27 and September 3, 8, 17 and 25. Field assistance was provided by Q. A. Aune, K. Donihoo, and G. Campbell, of the Division of Mines and Geology. The fractures described herein were first observed by geologists of the Department of Water Resources on August 5 or 6, following notification by the Butte County Disaster Office (Robert Akers, oral communication, 10/16/75).

GEOLOGIC SETTING

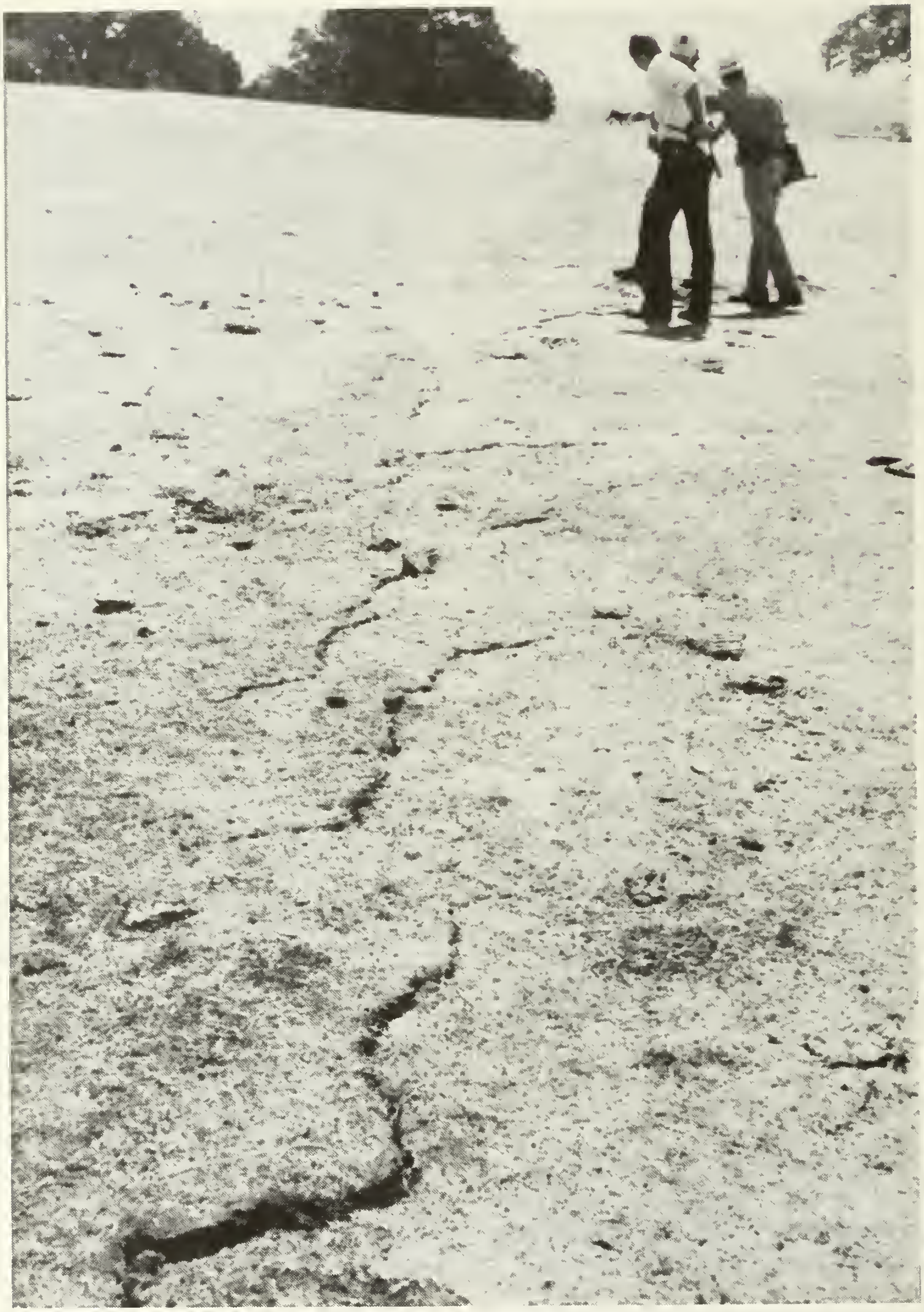
There are no known detailed geologic maps of the fault area. Generalized maps by Lindgren and Turner (1895) and Burnett and Jennings (1962) show the Cleveland Hill area to be underlain by metamorphosed volcanic bedrock but neither map depicts any faults in the vicinity of the newly formed fracture zone. The greenish metavolcanic bedrock in the immediate vicinity of the fault is covered largely with a soil mantle, probably less than 3 meters thick, and locally overlain by thin alluvial and colluvial deposits. The foliated bedrock fabric and structures generally strike north-south and dip steeply.

GROUND RUPTURE FEATURES

The linear distribution and abundance of fractures east of Palermo provide ample evidence that the ground fractures were caused by near-surface displacement along the Cleveland Hill fault. There, a well-developed en echelon, left-stepping pattern of fractures defines a very narrow, almost continuous zone that is traceable for a distance of 1.7 km. Other fractures are reported discontinuously for another 1.3 km to the north of the north end of the Cleveland Hill fault as mapped herein and are identified in the accompanying report by Akers and McQuilkin. It is not known if these northern fractures are associated with the Cleveland Hill fault.

The mapped fracture zone is seldom more than 3 to 5 meters wide. However, where the southern and central fault segments overlap, the fracture zone is about 50 meters wide and somewhat diffuse. Typically, the individual fractures are somewhat irregular in detail and are discontinuous to complexly connected at the ground surface. With a few exceptions, the fractures are less than 10 meters long. The fractures systematically trend 0° to 30° clockwise from the fault trend, averaging 15° from that trend. In tracing a specific fracture along its length to its termination, an observer must step to his left to pick up the next fracture of the fracture zone. This left-stepping pattern of fractures is persistent over 80-90 percent of the length of ground rupture zone. Ground fractures are observable only in the dry clayey soil. Figure 2, based on a compass, tape and pace survey, depicts the fractures along the southern fault segment in detail. These surface ground fractures are secondary features related to a more continuous feature at depth.

The type and amount of displacement along individual fractures varies from place to place. Some of the fractures have been modified by subsequent shaking, possible dehydration effects, and foot traffic. Nonetheless, as much as 3.5-4 centimeters of horizontal separation



Photograph 1. View south along the Cleveland Hill fault. Note the typical left-stepping en echelon pattern of ground fractures. The pattern is indicative of right-lateral offset of the underlying fault. Photo by T.C. Smith.

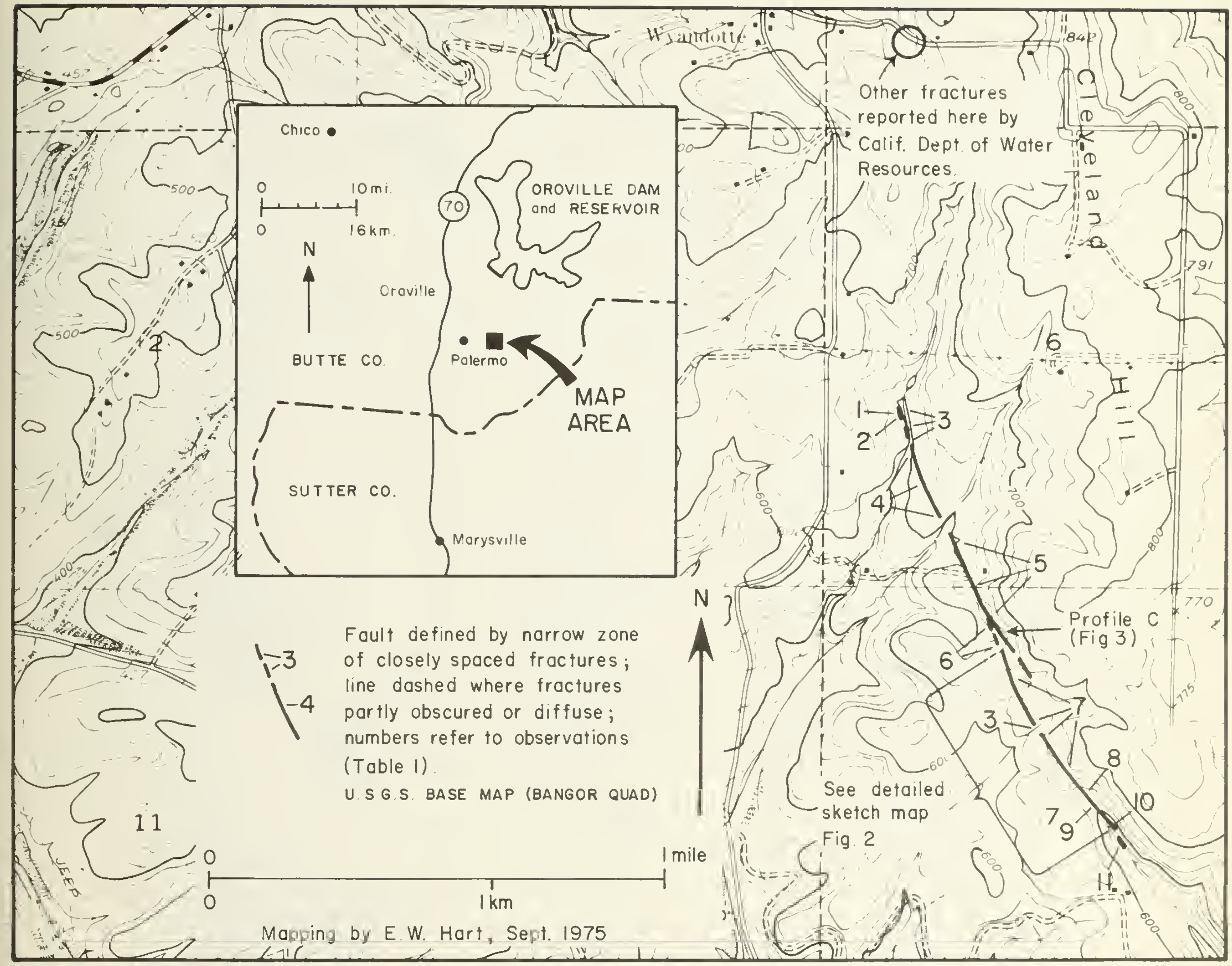
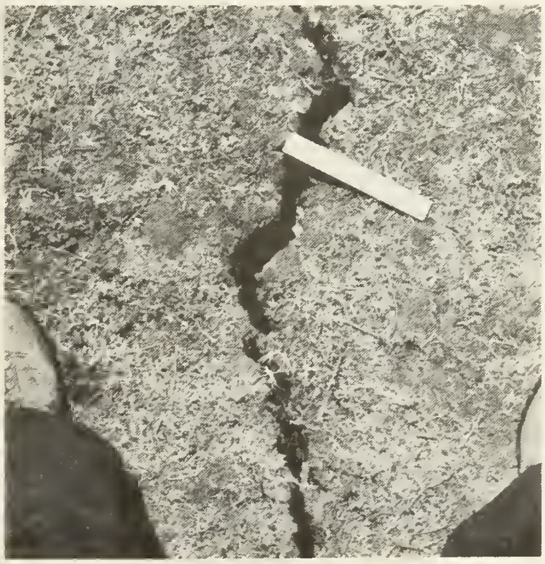

Wyandotte
842
457
Other fractures reported here by Calif. Dept. of Water Resources.
Cleveland
Hill
Chico
0 10 mi.
0 16 km.
N
OROVILLE DAM and RESERVOIR
70
Oroville
BUTTE CO.
Palermo
MAP AREA
SUTTER CO.
Marysville
500
400
600
700
800
791
770
775
2
6
1
2
3
4
5
Profile C (Fig 3)
6
3
7
8
10
7
9
11
3
4
Fault defined by narrow zone of closely spaced fractures; line dashed where fractures partly obscured or diffuse; numbers refer to observations (Table 1).
U.S.G.S. BASE MAP (BANGOR QUAD)
N
See detailed sketch map Fig. 2
11
JEEP
0 1 mile
0 1 km
Mapping by E.W. Hart, Sept. 1975

Figure 1. Map of Cleveland Hill fault as defined by ground fractures mapped during September 1975.



Photograph 2. Typical irregular north-trending ground fracture showing maximum horizontal separation (extension opening) of 2-3 cm and slight vertical offset. The bottom part of the photo, or the south-west side of the fault, is down. Photo by T.C. Smith.

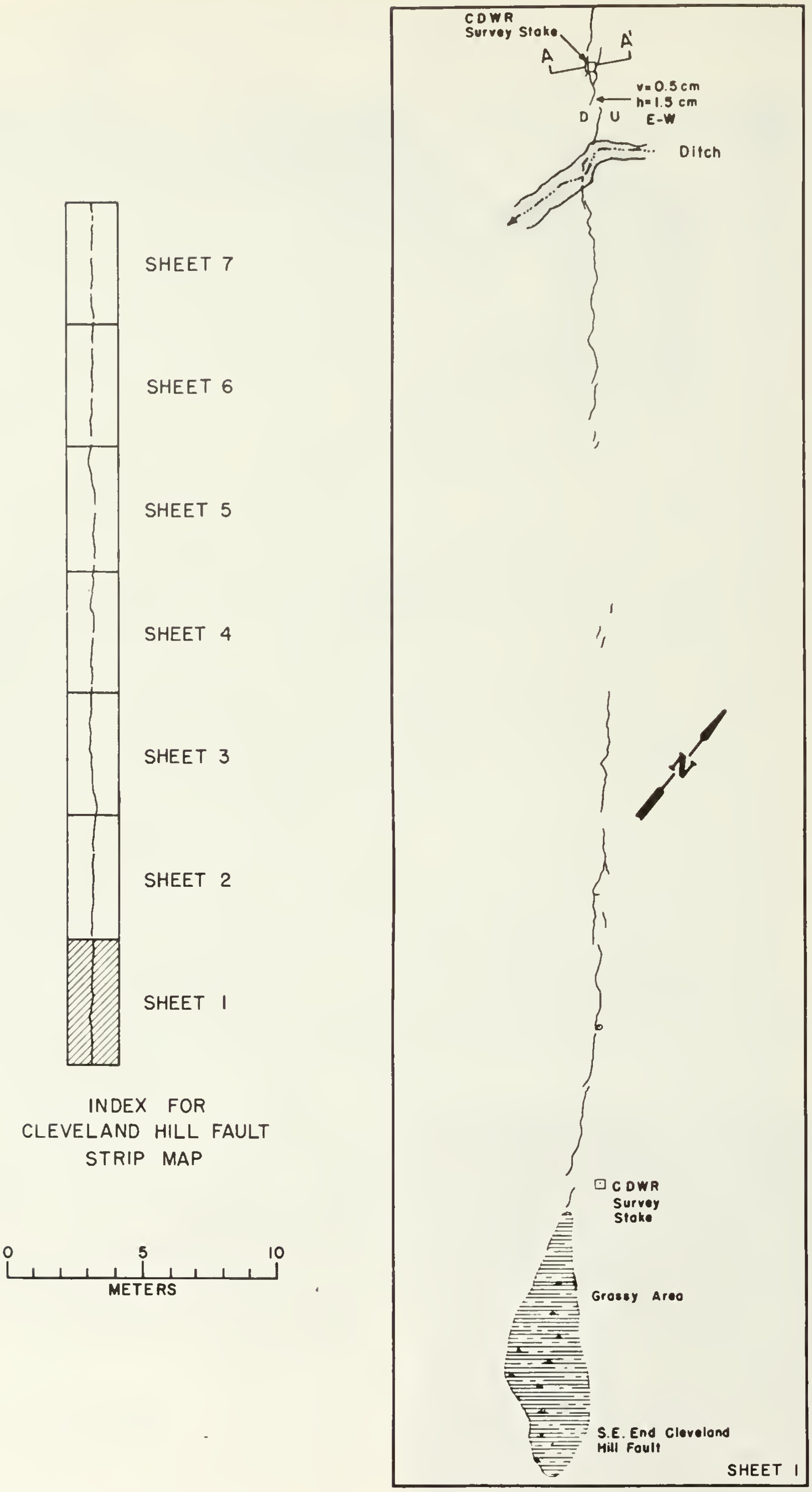
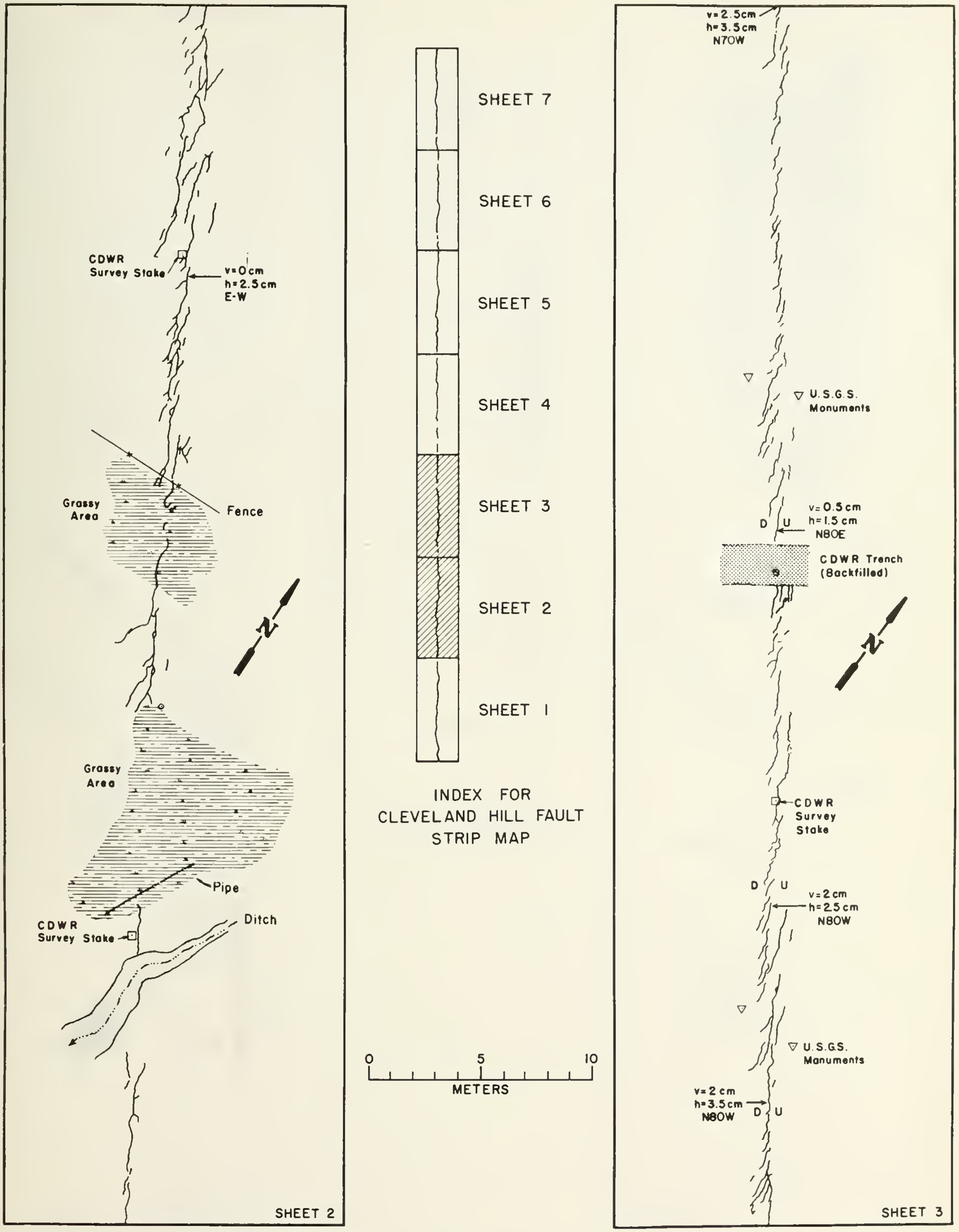


Figure 2. Compass, tape and pace survey of ground fractures along the Cleveland Hill fault. Fractures were mapped by J. S. Rapp during September 1975, assisted by E. Hart, Q. Aune, and P. Buchholz. Offsets measured on September 17 and 25. See Figure 1 for location.



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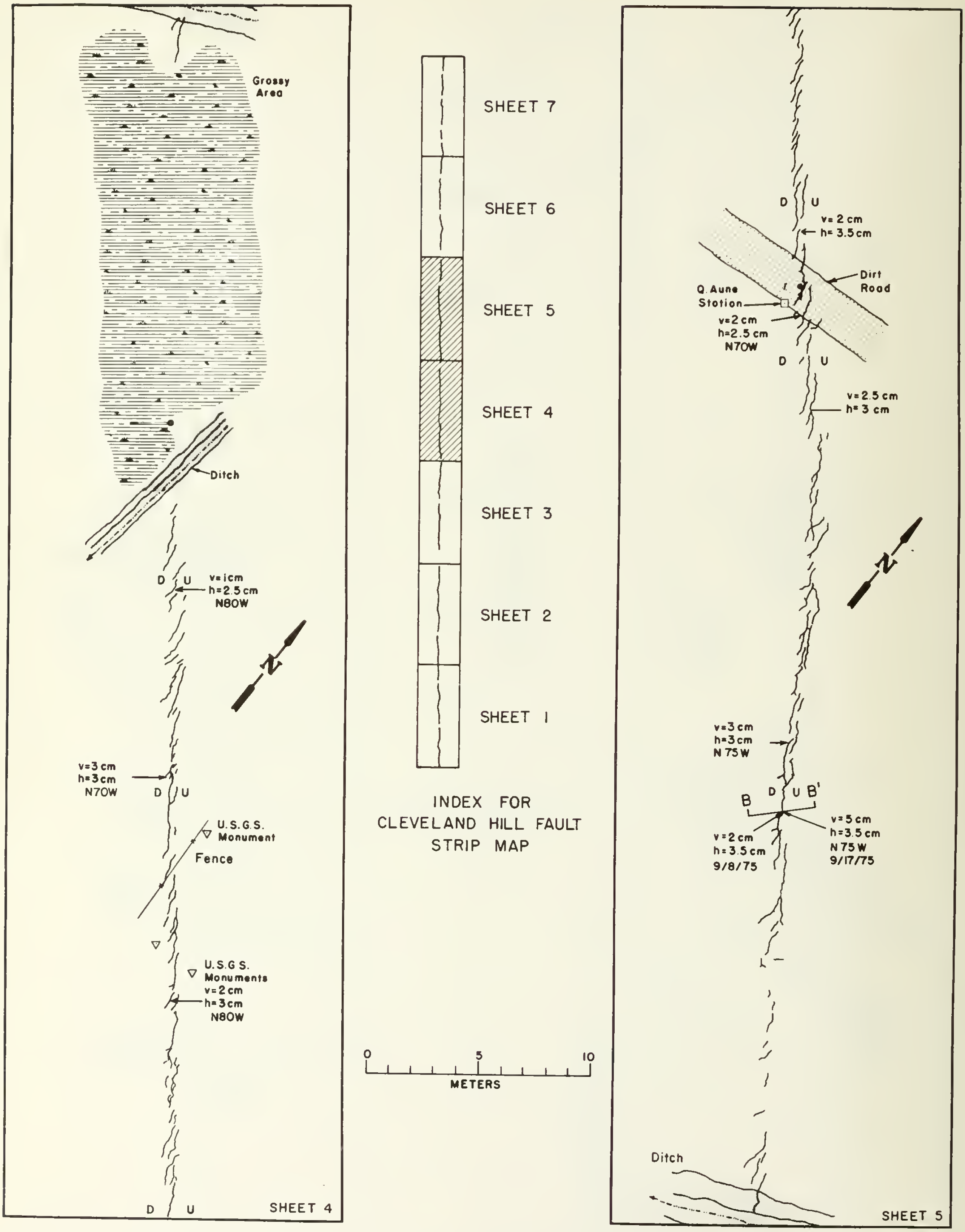

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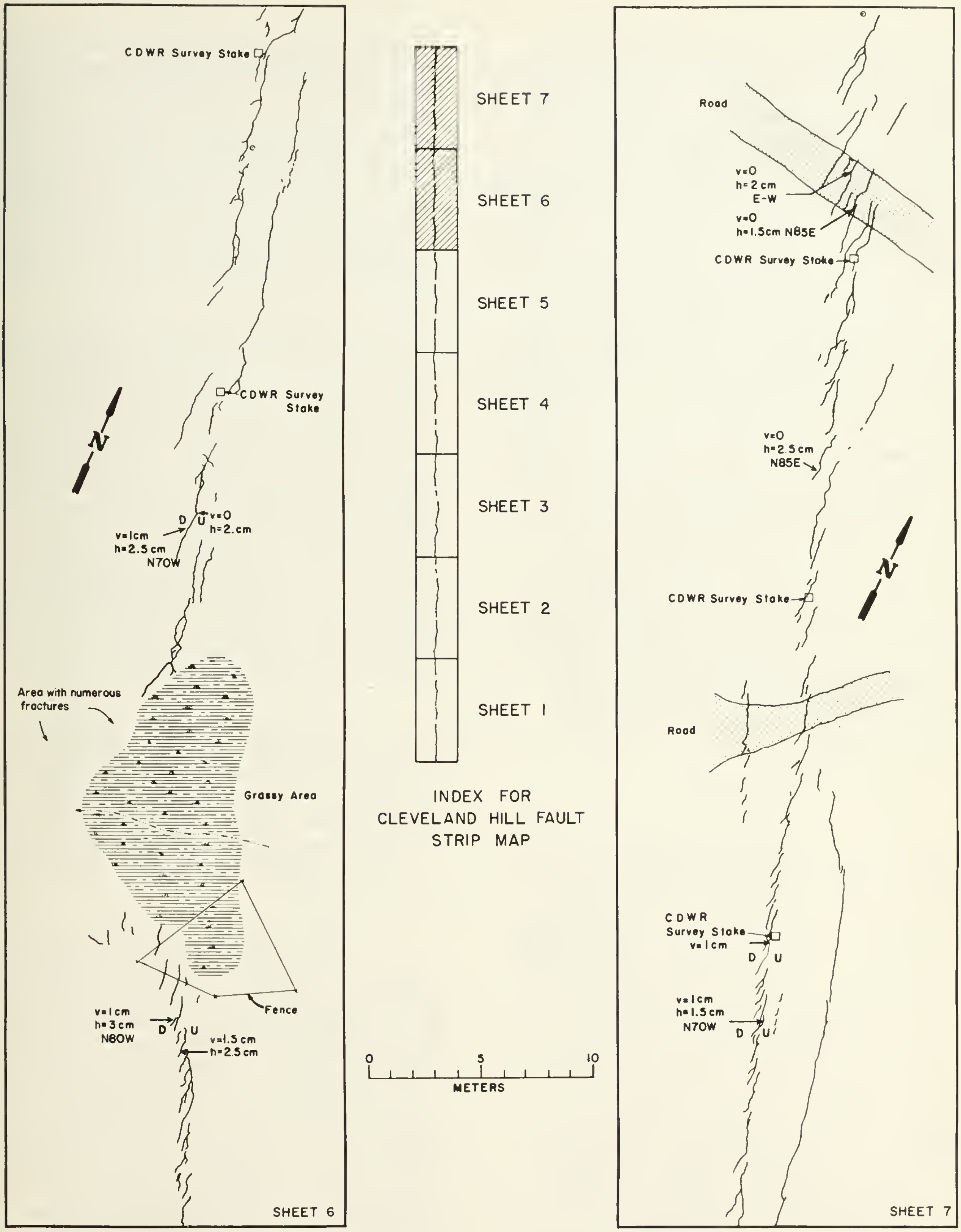

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(i.e. extension) was observed between matching points on opposite sides of some fractures, although most fractures showed much less displacement. The principal direction of fracture opening (i.e. horizontal separation) was N 80°W for the south and central segments of the fracture zone (figure 2). The direction of extensional opening and the orientation of the fractures with respect to the fracture zone indicates that the horizontal separation of the N 30° W-trending fracture zone consisted of both right-lateral and extensional components. Vertical separation (dip-slip displacement) was generally smaller or not evident at all on the individual fractures, although many fractures along some segments of the fracture zone showed the west side down. Fractures of the central and southern segments were vertically offset a maximum of 3-4 cm locally. One fracture was observed to have 5 cm of vertical offset (measured 9/17/75) and there was some evidence of increasing offset as 6 cm was measured 8 days later. A summary of field observations and evidence for displacement along different segments of the fault is given in Table 1, which is keyed to the map (figure 1).

OTHER EVIDENCE OF FAULTING

Evidence of a pre-existing fault exists for much of the length of the zone of recently formed fractures. The central part of the zone is marked by a modified, west-facing scarp 2-4 meters high (photo 3 and figure 3). The low ridges west of the fault also appear to be slightly offset in a right-lateral direction. The southern fault segment is marked by an alignment of springs and subtle differences in vegetation across the fault (photo 4) and by slight breaks in slope and other subtle topographic features. The northern segment is marked in part by a straight stream segment. Fault gouge in bedrock also was reported in exploratory trenches placed across the fracture zone by the California Department of Water Resources (Robert Akers, oral communication, 8/27/75). The general trace of the Cleveland Hill fault is observable on aerial photographs and on a side-looking airborne radar (SLAR) image as a subtle lineament, probably marked in part by the springs, vegetation, and subtle topography referred to above. However, this feature appears to be relatively subdued compared with other structural lineaments that define a wide north-trending zone that can be traced for tens of kilometers south of the Oroville area.

Other surface evidence for faulting is provided by a leveling survey carried out by the U. S. Geological Survey following the August 1, 1975 earthquake. This survey indicates about 17 cm of vertical offset (west-side relatively down) near Wyandotte, just north of and along the trend of the Cleveland Hill fault (Charles Bufe, U.S.G.S., oral communication, 10/9/75). A triangulation resurvey of existing bench marks reportedly did not indicate measurable horizontal separation. However, details of these surveys have not yet been published by the U. S. Geological Survey.

A depth, hypocentral locations of the August 1 earthquake and aftershocks (C. Bufe, oral communication, 10/9/75) indicate a complex north-striking, west-dipping fault zone. First motion studies of the aftershocks indicate that subsurface faulting was normal with the west side down.

It is not known when the Cleveland Hill fault was last active, although the subtle topographic features mentioned above suggest that the fault may have been previously active sometime during Quaternary time. Conversely, the lack of clear and detailed fault-produced topographic features indicates that the fault either has not been active during Holocene time or there has been a very low rate of displacement. Other on-going studies may provide better insight regarding the recent history of faulting.

CONCLUSIONS

Based on surface observations, it is

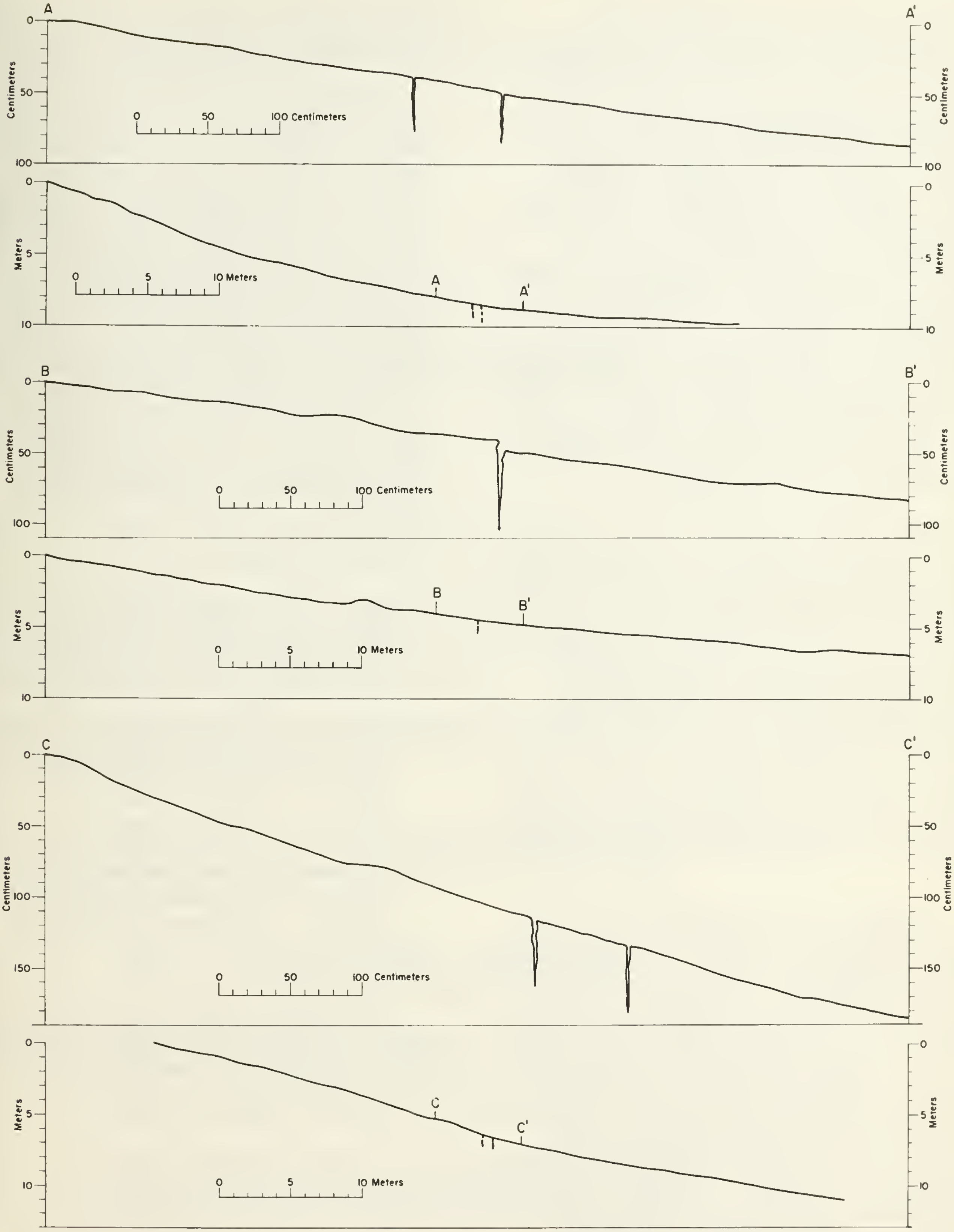

Figure 3. Leveling profiles across the Cleveland Hill fault. See Figures 1 and 2 for locations of profile locations. Each of the three profiles cross the fault at nearly right angles, N50°E. Note that the central parts of the profiles are shown at a larger scale. Surveyed by J.S. Rapp and G. Campbell, 9/25/75.

concluded that the Cleveland Hill fracture zone is the direct result of near-surface displacement along a pre-existing fault in bedrock. The well developed pattern of en echelon ground fractures indicate right-lateral strike-slip displacement virtually along the entire length of the mapped fracture zone. Because the fractures are secondary effects of faulting, the amount of horizontal displacement on the fault can only be measured indirectly. However, it is estimated that right-lateral displacement is about 3 to 4 cm for the central and southern fault segments. The north fault segment appears to have had a maximum right-lateral offset of 1 to 2 cm. The lack of notable offset of fences and other linear features also suggests that maximum horizontal displacement is limited to a few centimeters.

The measured maximum vertical offset for ground fractures was 4 to 5 cm for the central and southern segments. Other ground observations suggest that vertical offset was locally distributed over a zone 2 to 3 meters wide and vertical displacement may have been somewhat greater than measured. These latter observations were not verified by the 3 leveling profiles made across the fault, nor did any of the fences, dirt roads or water ditches reveal substantial vertical offset. The north fault segment did not display any measurable vertical displacement.

In summary, the Cleveland Hill fault is an oblique slip fault with both normal and right-lateral strike-slip components of displacement. The type of displacement and the N30°W orientation are compatible with the hypothesized subsurface faulting based on seismicity. It is possible that the Cleveland Hill fault is a subsidiary surface and near-surface element with a greater north-trending zone of faults which caused the Oroville earthquake of August 1, 1975. If the predominant faulting at depth is normal with the west-side down, as reported (C. Bufe, oral communication 10/9/75), then the faulting presumably resulted from east-west crustal extension. Thus, a northwest-trending fault within the seismic zone of faulting would be expected to have both right-lateral and normal components of displacement.

Although the Cleveland Hill fault does not appear to be a major active fault, it does pose a hazard to structures that might be built astride it. Moreover, it is apparently related to a larger zone of faults capable of producing at least moderate earthquakes that can pose other types of seismic hazards in an area formerly considered to be of relatively low seismicity. The fact that no historically active, or even Quaternary, faults were known in the Oroville area should give us ample reason to re-evaluate our knowledge of active faults in the Sierra Nevada foothills and other areas of California considered to be of minimal seismic potential.

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ACKNOWLEDGEMENTS

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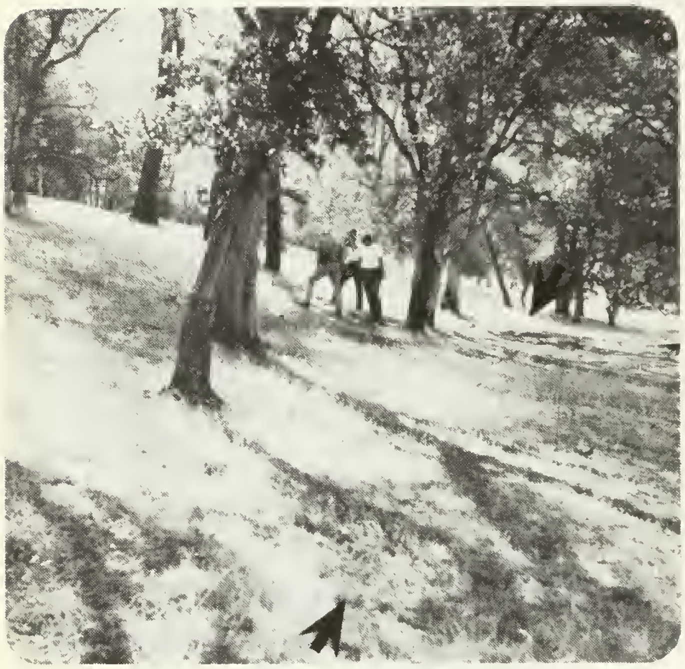
TABLE I

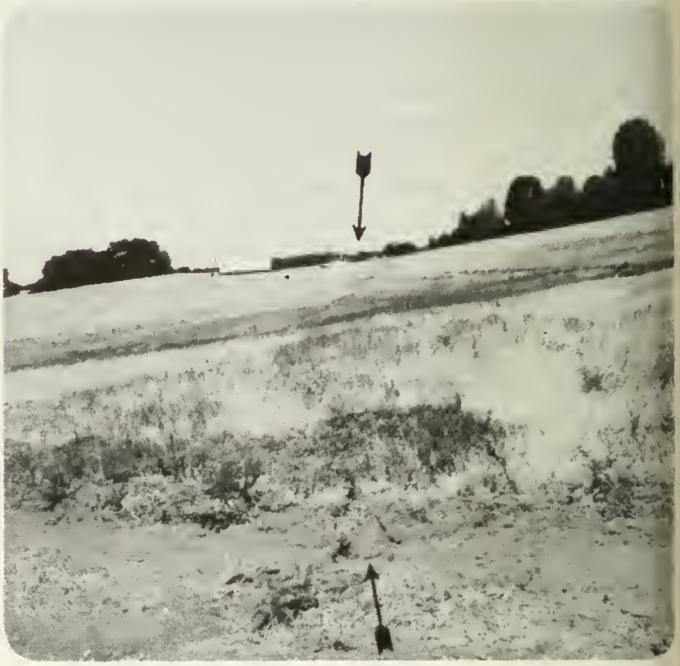
Summary of field observations of 8/27/75 and 9/3/75, Cleveland Hill fault. See figure 2 for fracture details of southern fault segment.

		Maximum apparent displacement (in cm)	
Map location	Field observations	Vertical *	Horizontal **
1	Most northerly observation of left-stepping en echelon fractures.	0	0.5 (E)
2	Minor parallel fractures (3) normal to earth-fill dam in zone about 8 meters wide; west fracture shows right-lateral offset of preserved soil surface.	0	0.5 (E)
3	Moist soil areas near creeks and springs; no fractures observed.		
4	Well defined zones of left-stepping en echelon fractures less than 3 meters wide.	0-1 (E)	1-2 (E)
5	Well defined zone of left-stepping en echelon fractures commonly at base of west-facing modified scarp; fracture zone diffuse and discontinuous to SE.	4	3-4
6	Diffuse zone of fractures about 50 meters wide, includes some left-stepping en echelon sets.	0?	2? (E)
7	Zone of left-stepping en echelon fractures less than 5 meters wide; zone locally coincides with vegetation alignment, springs and subtle breaks in west-facing slopes.	5	3-4
8	Water pipeline with apparent right-lateral offset on trend of fracture zone; questionable data as pipeline is sinuous.	?	3-6? (E)
9	Minor, discontinuous, en echelon fractures exposed in NW bank of ravine 1.5 meters deep; fractures dip 60-70^{o} to SW and align with surface ground fractures to NW and SE.	0.5	1-1.5
10	Most southerly extent of narrow, well-defined zone of fractures; left-stepping pattern weakly developed; zone aligns with springs and scarp.	?	1 (E)

Map location	Field observations	Maximum apparent displacement (in cm) Vertical *	Maximum apparent displacement (in cm) Horizontal **
11	Single, obscure north-trending fracture.	?	?



Photograph 3. View south of modified scarp of the Cleveland Hill fault. Recent ground fractures formed along the base of the scarp, which is indicated by the location of arrows. Photo by T.C. Smith.



Photograph 4. View north along Cleveland Hill fault. Note the change in vegetation along the strike of the fault. Several seeps are located along the fault, and their presence is indicated by thick patches of green grass and standing water. Note that the fault changes to a more northerly trend in the center of the photo. Photo by T.C. Smith.

*Fractures with vertical displacement (west side down) are exposed almost solely on west-facing slopes (gentle to moderate).

**Measured horizontal distance between matching points on opposite sides of open fractures; estimated displacement indicated by E.

SECTION 3

DAMAGE CAUSED BY THE OROVILLE EARTHQUAKE

OBSERVATIONS OF EARTHQUAKE RELATED BUILDING DAMAGE

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ABSTRACT

Structural damage to several schools and a hospital as well as other related observations are reported.

INTRODUCTION

The first earthquake as reported by the University of California, Berkeley at 9:27:17.6 a.m. local time Friday, August 1, 1975, was 5.0 Richter (R) magnitude with epicenter at 39° 28.0' north latitude and 121° 37.09' west longitude which was about five miles southwest of Oroville at a depth of about 7km. Dishes were reported broken. It was felt by a few people in Sacramento. It was also felt in Western Sierra County, Butte County and many Auburn residents felt it. Two aftershocks occurred, the maximum was 3.0 magnitude.

At 1:20:94.3 p.m. the same day a stronger shock occurred. It was reported at 5.7 R to 6.4 R by various sources. The epicenter was 39° 27.1' north latitude, and 121° 35.6' west longitude or about 5½ miles SW of Oroville at a depth of about 5km. This was rather strongly felt throughout Sacramento. The press reported it was felt in Fresno, Tahoe and San Francisco.

By 4 p.m. that day an EERI/DMG Information Clearinghouse was established at the Oroville Division of Forestry Office which is also a firehouse with 24-hour telephone service. Early press reports indicated many injuries and considerable damage throughout Oroville and Thermalito.

BIRD STREET SCHOOL
Built 1867 and rebuilt in 1912

Two Corinthian column capital decorations of clay tiles were dislodged from the top of the columns, one of which was directly over the main entrance as shown in Figure 1. Two windows were broken which may have been the result of the earthquake.

There was considerable plaster damage to the walls and ceiling throughout the building. It was obvious that the walls and ceilings moved separately as evidenced by the continuous cracks in the ceilings adjacent to the walls as shown in Figure 2. Pieces of ceiling plaster fell in the auditorium, second floor classrooms and basement stair ceilings as shown in Figure 3. Earthquake motion at this site was not sufficient to throw books from the shelves in the storage room on the first floor, however, a wash bowl was thrown off the wall in the cafeteria building as shown in Figure 4.

BURBANK SCHOOL

During the first visit on August 2 the east wall of this one-story brick pre-Field Act school building, built in 1925, was observed to be seriously damaged.

This brick wall shown in Figure 5 bulged dangerously outward several inches for a length of about ten feet in the center at the level of the roof. During the second visit on August 5, this east wall appeared to have moved out a bit further and a portion of the north wall was bulging in a similar manner but of lesser amount. The east wall was separating between the two brick wythes although they were tied with metal strips as shown in

Figure 6. A 5.0 magnitude earthquake occurred on August 7 and knocked off several bricks as shown in Figure 7 taken during the August 8 visit. This wall was anchored to the roof framing with the type of wall anchor as shown in Figure 8.

Ceiling plaster fell in the corridor as shown in Figure 9.

A decorative ornament fell from the west gable end wall between the August 2 visit and the August 5 visit.

The damage in a post-Field Act wood frame school constructed in 1947 at this site consisted of only very minimal plaster cracks and several concentric ring light fixtures were tilted and hanging with one or two wires. One such ring fell to the floor. Damage of this type can be prevented simply by twisting the wire hangers as usually shown on the approved drawings but are frequently straightened to remove the rings for cleaning purposes.

EASTSIDE SCHOOL

A pre-Field Act school building, built in 1925, sustained nominal plaster damage in the corners of the walls and at the junction of the wall and ceiling in several locations. One light fixture grill was hanging vertically suspended by one of the safety chains as shown in Figure 10. This building was of somewhat similar design as that of the Burbank School. In fact, both were built by the same contractor under the same contract 50 years ago. Post-Field Act buildings on this site sustained no damages except possibly some very light plaster cracks.

CENTER SCHOOL

All buildings on this site were of post-Field Act construction. The only observed damage was several concentric ring light fixtures which were tilted and hanging with one or two hanger wires instead of three. Some light exterior plaster cracking was noted at several corners of the buildings and some of the contents of several storage shelves were spilled to the floor.

A new concrete block masonry building had just been constructed on this site and opened in the fall semester of 1975. No damage of any kind could be found.

LAS PLUMAS HIGH SCHOOL

This is a rather large recently constructed complex. The four-inch wide plastic light fixture lenses were dropped to the floor throughout the site and at least two light tubes fell to the floor. Seismic expansion joints throughout the site did not indicate any movement. Two panes of glass were broken in the Auto Shop.

The gymnasium contains a west wall added later to close-in the end of the building. This wall is of wood stud construction, plastered on each side and is not a structural wall. The plaster appeared to have been cracked prior to the earthquake because the cracks were in both horizontal and vertical directions. The plaster appeared to have bulged about one-eighth of an inch at mid-height opposite the control joints. Several windows were flipped out hanging by the operating device as shown in Figure 11

OAKDALE HEIGHTS SCHOOL

This site is just down the street a short distance from Las Plumas and is also of recent construction. The light fixtures here were the same design as those at Las Plumas High School, however, no light lens damage occurred here because they were not installed. One window was broken, probably the result of the earthquake. No damage of any other kind could be found here.

OROVILLE HIGH SCHOOL

Several plastic light fixture lenses fell to the floor or desk tops in the classrooms.

A fluorescent light tube fell to the floor in the shop. It was noted that the overhead door suspension system in the shop was very similar to that which dropped the doors in the Palermo Firehouse. The school officials advised that they would place bracing on the overhead tracks to prevent their spreading during future seismic disturbances.

Plastic light fixture lenses fell to the floor in several portable buildings on this site as shown in Figure 12. The T-bar ceilings were also displaced in several of these portable classrooms.

The Maintenance Building, a non-school purpose building and not constructed under the provisions of the Field Act, had several cracks in the masonry walls. Some cracks were old and others were probably the result of the earthquakes. School officials indicated that the building would be demolished in the near future.

PALERMO ELEMENTARY SCHOOL

This is a post-Field Act school located in Palermo which is about four or five miles due south of Oroville and is within a mile of the epicenter of the largest shock. A window was possibly broken here due to the quake. Several light fixtures were damaged. It is understood that the light fixtures had been replaced by the school district without Office of Architecture and Construction approval as permitted under the $10,000 exemption in the Field Act.

Plaster was cracked all around the junction of the walls and ceiling of the multipurpose platform. This building was built in 1951. The roof diaphragm of the platform is of diagonal sheathing and has a span/depth ratio of about 3:1. Currently the span/depth ratio of diagonally sheathed horizontal diaphragms allowed in Title 21 California Administrative Code is limited to a maximum of 2:1 because of its flexibility as learned in the tests made in the early 1950's.

ST. THOMAS CHURCH AND SCHOOL
(Not under Field Act supervision)

On the August 2 visit several bricks were displaced from the church bell tower and the upper portions of the wall were cracked. The upper portion of the unreinforced brick chimney was knocked off. During the August 5 visit it was noted that several bricks fell out of the bell tower.

No damage was found in the school. Sport trophies, similar to those that fell at the Rio Dell Elementary School during the June 7, 1975 Fortuna earthquake, were not dislodged.

COURTHOUSE (Downtown)

The old portion of the courthouse and jail was cracked rather heavily and was vacated. The walls of this building appeared to be stuccoed masonry construction.

From a casual review no damage was observed in the new portion of the courthouse probably built five to ten years ago.

SUPERIOR COURT BUILDING

This building was very recently constructed. Books were thrown to the floor and the bookcases were damaged. The concealed T-bar ceiling was damaged at several locations, most of which occurred around the perimeters in several rooms.

BUSINESS DISTRICT

A few, perhaps 5 percent to 10 percent, of the window panes were broken in the store fronts. T-bar ceilings were damaged, particularly around the perimeters of the rooms. Several such ceilings had diagonal bracing wires installed within the system. In a department store the hangers became disconnected allowing the ceiling to bulge or drop downward several inches in several places. In one instance the nail anchoring the hanger wire pulled out, in other instances it appeared that the bends formed in the hanger wire to level the ceiling had straightened out. A woman narrowly missed being hit by a falling T-bar in a clothing store dressing room. Pictures on the walls were askew or fell to the floor. Merchandise was thrown to the floor from shelves. Masonry walls were cracked in several buildings. Unanchored brick veneer was dislodged and on the verge of falling. In general, from a casual review, the damage was not readily apparent. That is, the streets were not littered with debris.

MEDICAL CENTER HOSPITAL

This is basically a one-story hospital but a portion on a side hill was two stories. The Hospital Administrator, Mr. Paul R. Hoff, was very pleased with the performance of the portion of the hospital emergency wing just recently constructed under the provision of 1973 Alquist Hospital Act. The only damage in that portion consisted of a crack in the hall ceiling plaster and several escutcheons around the sprinkler heads, which are merely held by friction, fell to the floor. No other damage could be found.

Nonstructural plaster damage occurred in several areas throughout the older portion of this hospital, the oldest of which was probably about ten years old. In the pharmacy and storage areas many bottle containers and other medications were damaged when they were thrown to the floor. Strips of adhesive tape were placed on the front of these shelves to prevent further loss as shown in Figure 13. Mr. Hoff strongly recommended that regulations be adopted which will require some means of retaining critically needed drugs and medications on the shelves in hospitals.

This hospital has two basic exterior sources of electricity and when the original hospital was constructed the administrators considered requesting a waiver for the requirement of an emergency generator. The earthquake knocked out both sources of service and their emergency generator was required to continue to operate for about two hours due to intermittent source electrical service.

The generator was mounted on the top of steel channels placed on a slab on grade. No anchor bolts were provided into the slab. Mr. Hoff indicated they would install anchor bolts in a few days.

The oxygen tank became displaced. It was about 4 feet diameter and about 12 feet high and installed at the time of the original construction. The tank was supported by three legs and the anchor bolts were about five-eighths of an inch in diameter. Two such anchor bolts were pulled out of the concrete but appeared to penetrate the concrete only about an inch as shown in Figure 14. One of the anchors held and the other two pulled out, thus allowing the tank to rock and rotated about one-half an inch. Mr. Hoff took immediate steps to anchor the tank.

Mr. Hoff estimated that only one or two patients were treated at this hospital from earthquake related injuries.

PALERMO FIREHOUSE

This Division of Forestry firehouse was of recent construction - probably about three or four years old. Walls were tilt-up concrete and were lightly cracked at one passthrough doorway and a horizontal crack occurred in mid-height of the adjacent wall panel.

Two overhead doors fell out of their tracks on top of the fire engines. The three-inch long axles supporting the door on the horizontal overhead track came out of their housing as there was no retainer at the rear end of the axle and the track was free to deflect laterally, thus allowing the doors to fall on top of the fire engines.

BULLARDS BAR DAM

A fisherman on the reservoir behind Bullards Bar Dam reported a single wave about a foot in height crossed the lake about 9:30 a.m., August 1, 1975. There was no wind thus the water was smooth.

OROVILLE RESERVOIR

The ranger at the Visitor's Center reported that most of the people on the lake at the time of the earthquakes were not aware of any special wave action or that an earthquake had occurred. One person did, however, report he noticed an unusual wave - perhaps about a foot high - at the time of the afternoon shake. He had just launched his boat and pushed off when the wave came by.

OBSERVATIONS

(1) Once again it was clearly shown that Structural Safety Section enforcement of the Field Act requirements reduces the likelihood of structural damage to public school buildings in the event of an earthquake.

(2) Prior to the earthquake the Oroville City Elementary School District applied for permission to continue the use of the pre-Field Act school buildings at Bird Street, Burbank and Eastside Schools until June 30, 1977 as allowed under Section 15516 of the Education Code. After the earthquake the school board withdrew their application and elected not to allow students or teachers in these buildings.

(3) This earthquake was the first test of the effectiveness of the Alquist Hospital Act as evidenced by the highly successful performance of the addition constructed under its provisions at the Medical Center Hospital.

(4) Current methods of installing T-bar ceiling systems do not perform adequately in earthquakes. This has been demonstrated repeatedly.

(5) Consideration should be given to the effect of vertical and horizontal acceleration on all overhead items such as light fixtures, lenses, grilles, etc.

ACKNOWLEDGMENTS

Reviewed by F. W. Cheesebrough and W. L. Pattillos.

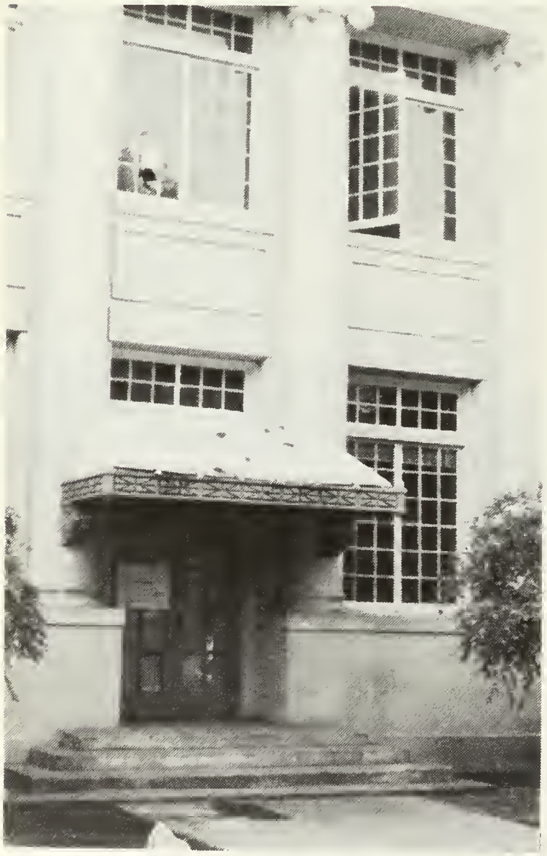

Fig. 1. Bird Street School
Portion of column fell at
the main entrance

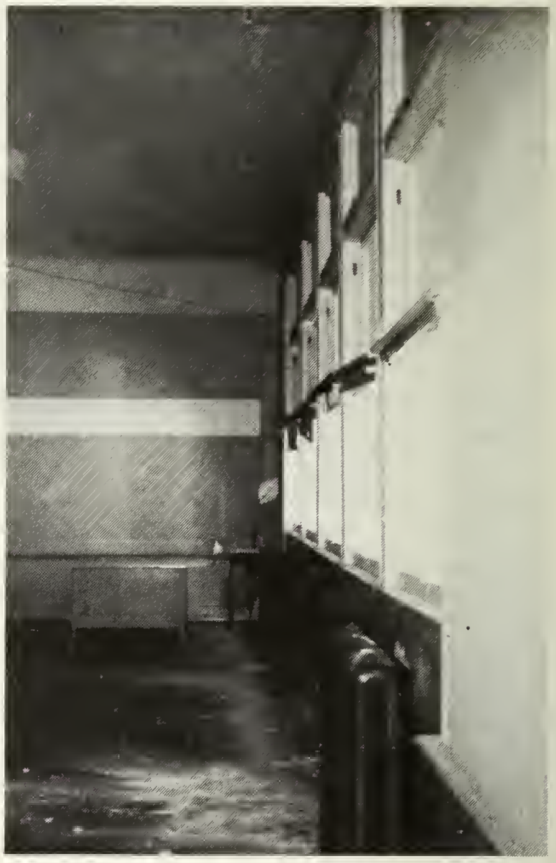

Fig. 2. Bird Street School
The wall and ceiling separated
on the second floor

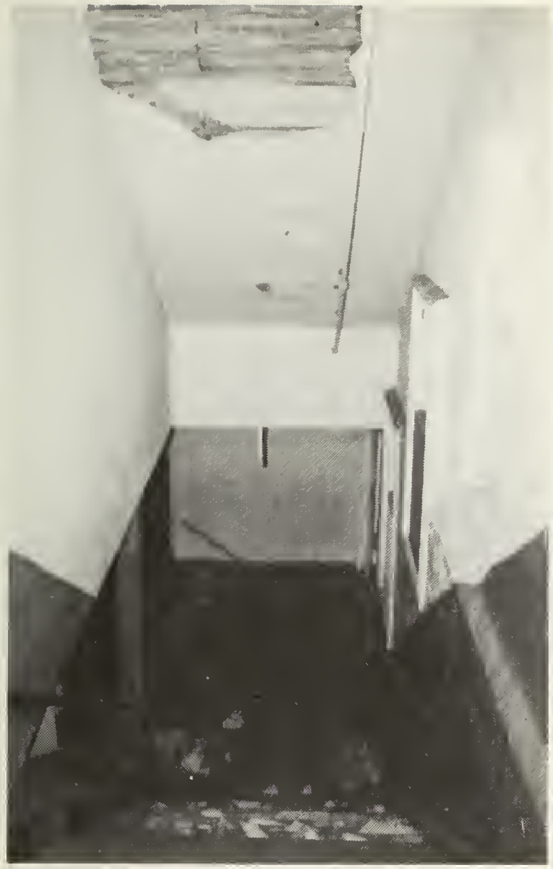

Fig. 3. Bird Street School
Portions of ceiling plaster
fell on stairway

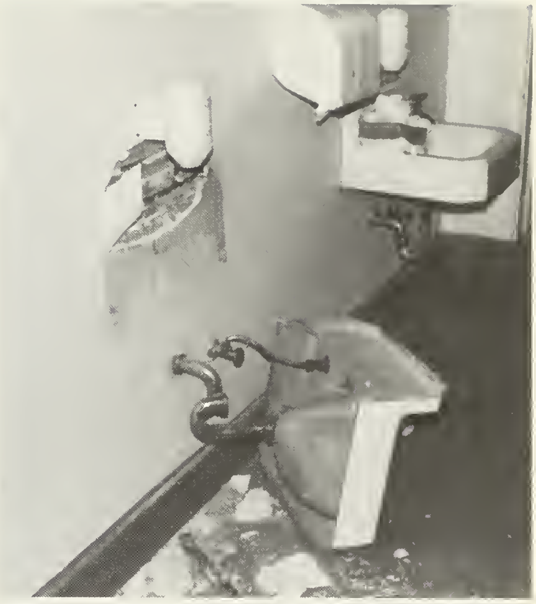

Fig. 4. Bird Street School
The washbowl fell off the wall

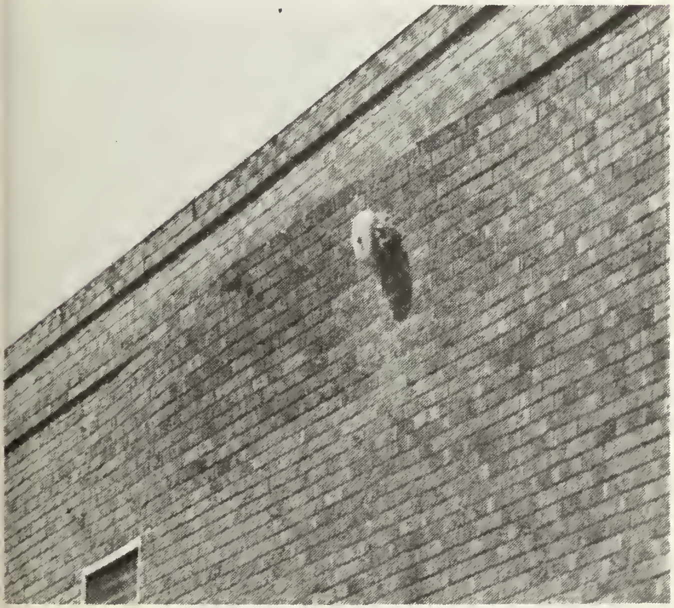

Fig. 5. Burbank School
East wall bulged.
Photo taken August 2.

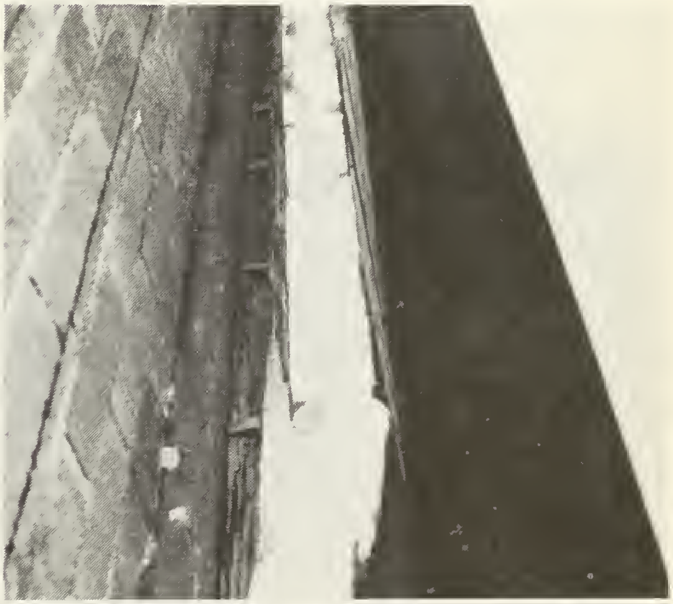

Fig. 6. Burbank School
Ties between the two wythes of
brick did not hold wall together.
Photo taken August 5.

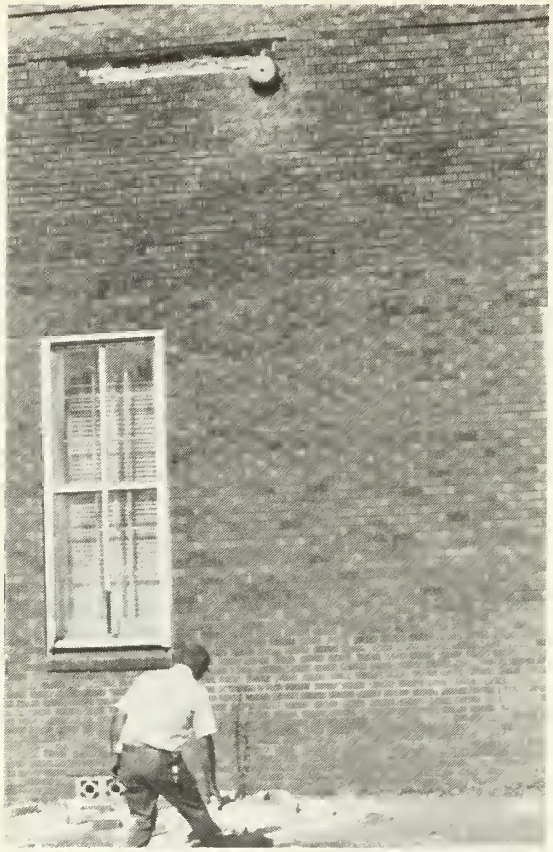

Fig. 7. Burbank School
Several bricks fell from wall
during an aftershock.
Photo taken August 8.

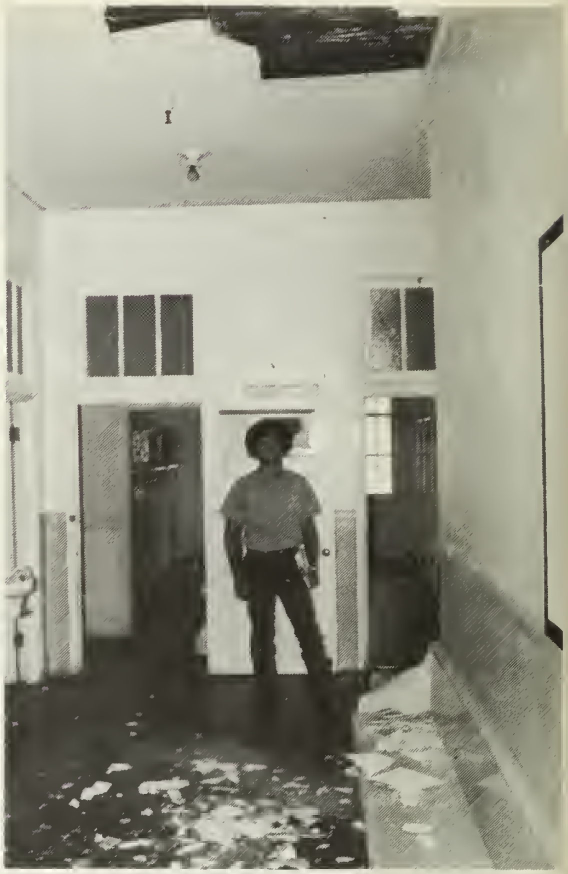

Fig. 9. Burbank School
Ceiling plaster on wood lath
fell in the corridor

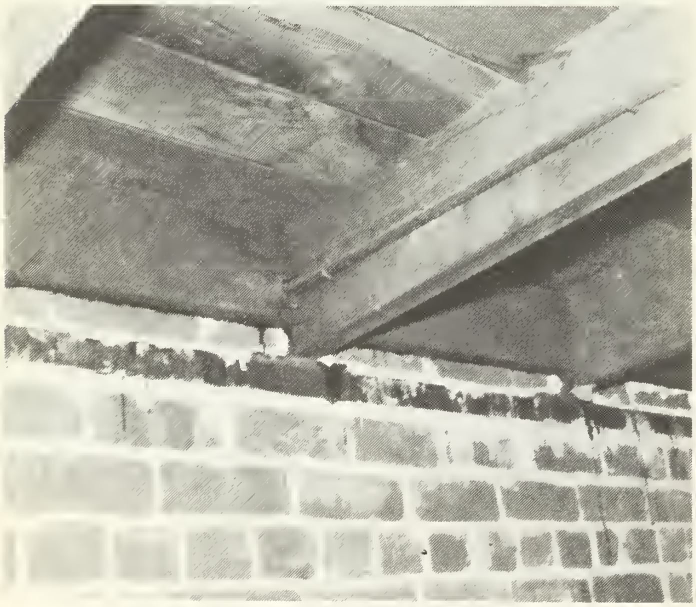

Fig. 8. Burbank School
Wall to roof anchors used
at this site were spaced
6 to 8 feet apart.

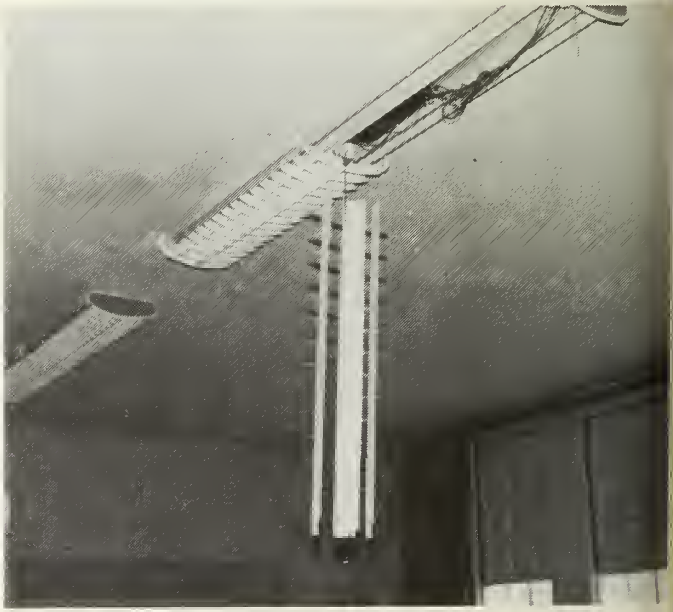

Fig. 10. Eastside School
Light fixture grille would have
fallen to the floor except that
one of the safety chains held.

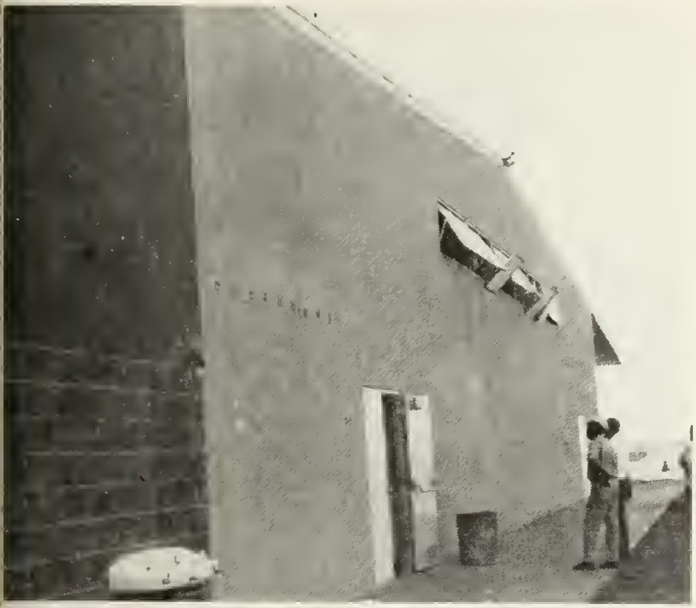

Fig. 11. Las Plumas High School
Several windows were hanging by their operating devices.

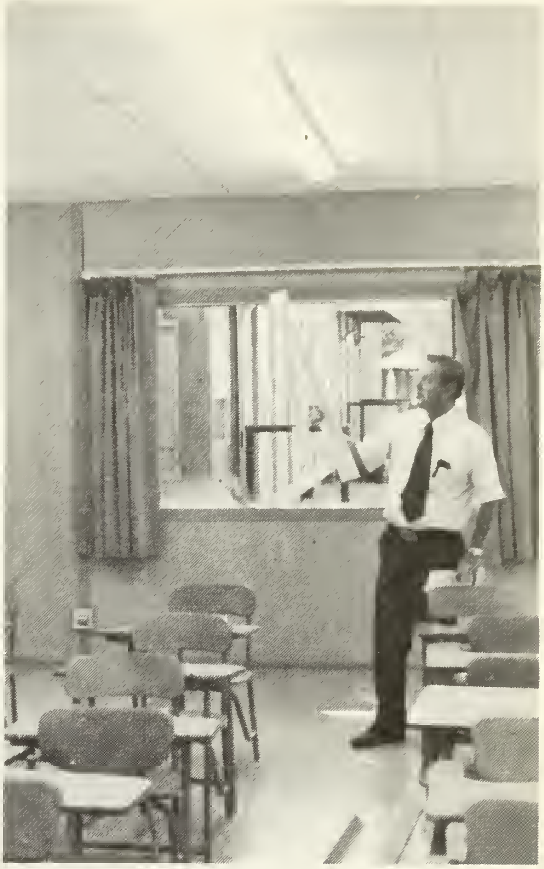

Fig. 12. Oroville High School
Light fixture lenses fell and some ceiling tiles were displaced in these portable buildings.

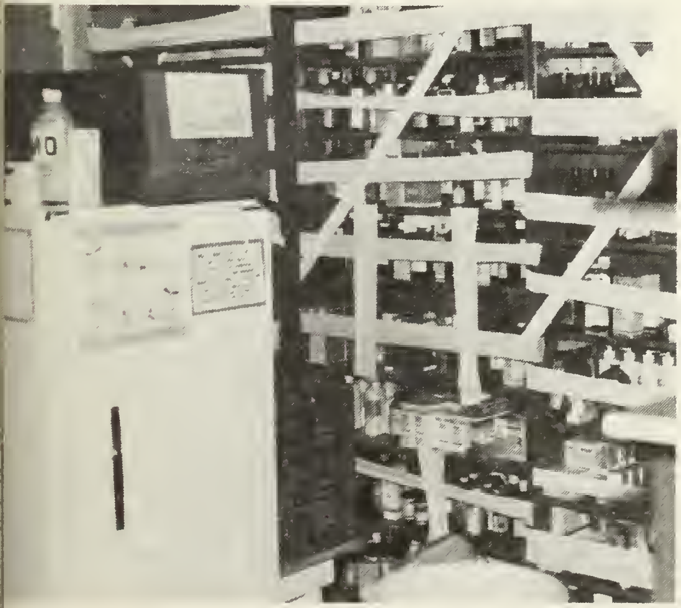

Fig. 13. Medical Center Hospital
Pharmaceutical and bottle goods were thrown to the floor. Tape was added to the shelves to prevent further loss.

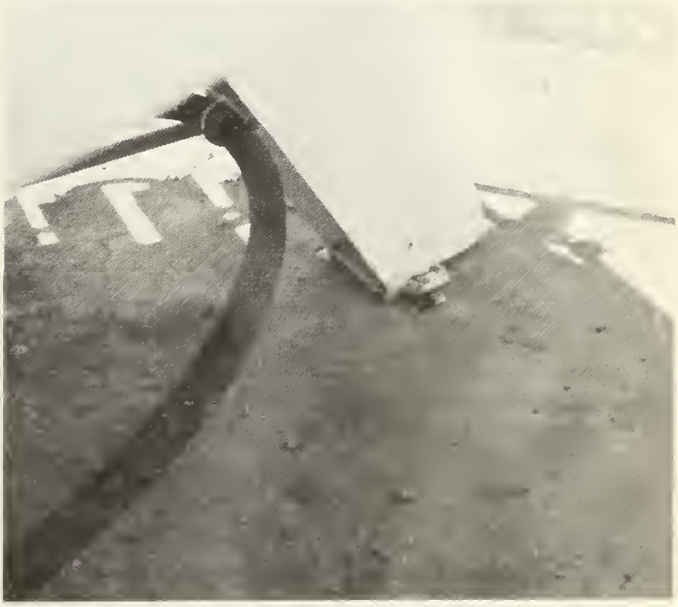

Fig. 14. Medical Center Hospital
Oxygen tank anchor failed.

EFFECT OF OROVILLE EARTHQUAKE ON STATE WATER PROJECT FACILITIES

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ABSTRACT

The effects of the foreshocks, aftershocks and the main shock of the Oroville earthquake that occurred at 1320 Pacific Daylight Time on August 1, 1975, on those State Water Project facilities that are located near the vicinity of the shock epicenters are discussed herein.

Inspections by Department of Water Resources personnel commenced following the 3.6 magnitude foreshock occurring at 0845 PDT and then were intensified immediately following the 5.7 magnitude main shock. Minor damage was observed on some of the facilities but none affected their safety or operation. Those areas with minor damage will be repaired by normal scheduled maintenance operations.

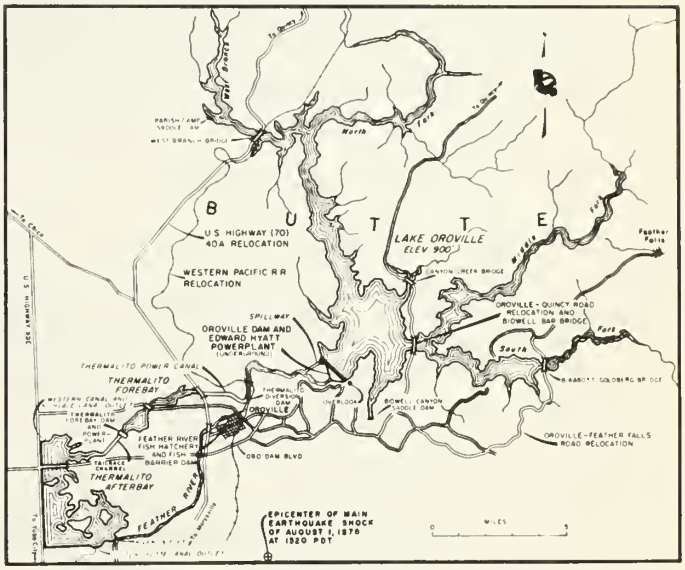
To Quincy
West Branch
PARISH CAMP SADDLE DAM
WEST BRANCH BRIDGE
North
Fork
To Quincy
B U T T E
U S HIGHWAY (70) 40A RELOCATION
LAKE OROVILLE ELEV 900'
Middle
Fork
Feather Falls
To Chico
WESTERN PACIFIC R R RELOCATION
CANYON CREEK BRIDGE
U S HIGHWAY 99E
SPILLWAY
OROVILLE DAM AND EDWARD HYATT POWERPLANT (UNDERGROUND)
OROVILLE - QUINCY ROAD RELOCATION AND BIDWELL BAR BRIDGE
South
Fork
THERMALITO POWER CANAL
THERMALITO FOREBAY
THERMALITO DIVERSION DAM
OROVILLE
OVERLOOK
BIDWELL CANYON SADDLE DAM
B ABBOTT GOLDBERG BRIDGE
WESTERN CANAL AND ... CANAL OUTLET
THERMALITO FOREBAY DAM AND POWER-PLANT
FEATHER RIVER FISH HATCHERY AND FISH BARRIER DAM
ORO DAM BLVD
OROVILLE-FEATHER FALLS ROAD RELOCATION
TAILRACE CHANNEL
THERMALITO AFTERBAY
FEATHER RIVER
To Marysville
To Yuba City
EPICENTER OF MAIN EARTHQUAKE SHOCK OF AUGUST 1, 1975 AT 1320 PDT
MILES
0
5

Figure 1. Location Map of Oroville Facilities

INTRODUCTION

Oroville Dam and 3,537,557 acre-foot ($4,363,536,000\ m^3$) Lake Oroville with their auxiliary facilities, are the keystones of the State Water Project (Figure 1). Oroville Dam's major function is to conserve and regulate flows of the Feather River for preferred release to the Sacramento-San Joaquin Delta, where the flow can be diverted by various facilities of the State Water Project and also provide salinity control against the intrusion of saline water from the ocean.

Some of the additional functions incorporated in the planning concept of the Oroville facilities were flood control protection for downstream communities and developed land, hydroelectric power, and recreational development. The environmental and economic impact on the surrounding and other affected areas were also considered in initial project planning.

The earthquake effects described herein will treat the major components of the Oroville complex and some of their appurtenances. The Oroville facilities were designed to resist earthquake forces in accordance with the state of the art of earthquake design as it existed during that era of 1957 to 1963. Assisting Department of Water Resources design staff in keeping in step with the state of the art were boards of consultants, experts in the design of dams, structures, and earthquake analyses. A consulting board presently consisting of Wallace L. Chadwick, internationally known civil engineer; Thomas M. Leps, prominent consultant in soil mechanics, foundations, and civil engineering related to hydroelectric development; Dr. Philip C. Rutledge, a pioneer in the fields of soil mechanics and foundations; and Alan L. O'Neill, a geological expert; are advising on dam related matters. Another board consisting of Dr. Clarence R. Allen, professor of geology, California Institute of Technology; Dr. John A. Blume, president of John A. Blume and Associates; Dr. Bruce A. Bolt, director of seismic stations and professor of seismology, University of California at Berkeley; Dr. George W. Housner, professor of civil engineering, California Institute of Technology, chairman; and Dr. H. Bolton Seed, professor of civil engineering, University of California at Berkeley, are consulting on earthquake related matters. All of these persons have received worldwide recognition for work in their respective fields.

EARTHQUAKE EFFECT ON FACILITIES

Oroville Dam and Spillway

Inspections of Oroville Dam and Spillway and reading of instruments were initiated by Department of Water Resources personnel following the 3.6 magnitude foreshock that occurred at 0845 PDT on August 1, 1975. Immediately following the 5.7 magnitude main shock of the Oroville earthquake occurring at 1320 PDT of the same day, additional inspection teams were dispatched to evaluate the effect of the earthquake on all Oroville facilities. Much of the initial attention focused on the 80,000,000 cubic-yard (61,164,700 m^3) zoned, earthfill embankment 770 feet (234.7 m) in height (Figure 2).

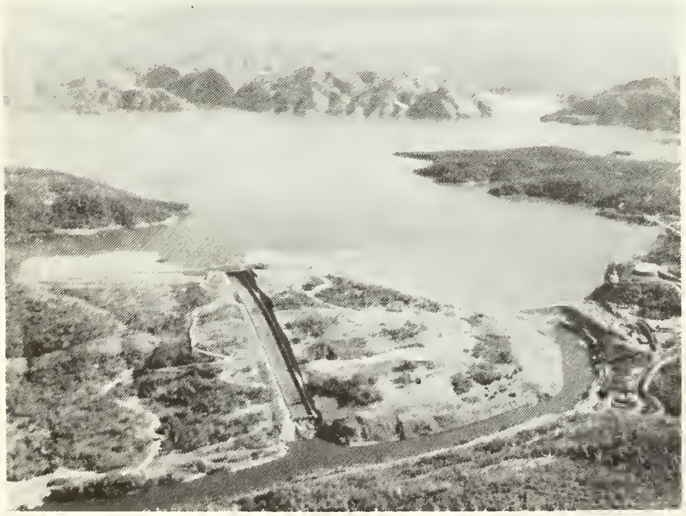

Figure 2. Oroville Dam and Lake Oroville

The dynamic instrumentation (Figure 3 for the Oroville Dam includes pore press cells, accelerometers and stress cells. The accelerations in the dam were measur by three-component accelerometer transducers. Accelerometer No. 3 located on rock at the downstream toe of the dam recorded a maximum value of 0.09 g perpendicular to the axis of the dam during the main shock. Accelerometer No. 4, located at the crest of the dam, also recorded a maximum value perpendicular t the axis of 0.09 g. Very little magnification occurred between the toe and crest during the first three seconds of strong shaking. After the strong shaking subsided, accelerometer records indicated magnification factors increased up to approximately 7.0. Other lower magnitude foreshock and aftershock records all depict strong magnification factors immediately after the instruments were triggered. On August 5, 1975, an aftershock of 4.6 magnitude showed a magnifica tion of approximately 10 between the base and the crest with the crest experiencing 0.26 g acceleration. Parallel to the axi of the dam, accelerometer No. 3 recorded maximum acceleration of 0.13 g and No. 4 at the crest recorded a maximum acceleration of 0.07 g. The reduced acceleration recorded at the crest occurred during the first three seconds and then acceleration magnifications in the order of 2 occurred at the dam's crest.

Accelerometer No. 3 also recorded a maximum vertical base acceleration of 0.09 g and No. 4 recorded a magnified acceleration of 0.15 g at the crest. After the initial strong shaking, the magnification factors increased and were in the order of 4.0.

Also on the crest of the dam next to accelerometer No. 4 is a strong motion instrument that recorded approximately the same accelerations as accelerometer No. 4. In the grout gallery a strong motion instrument also recorded similar aftershock accelerations as accelerometer No. 3. To provide better coverage should another event occur, one accelerometer will be added to each abutment of the dam.

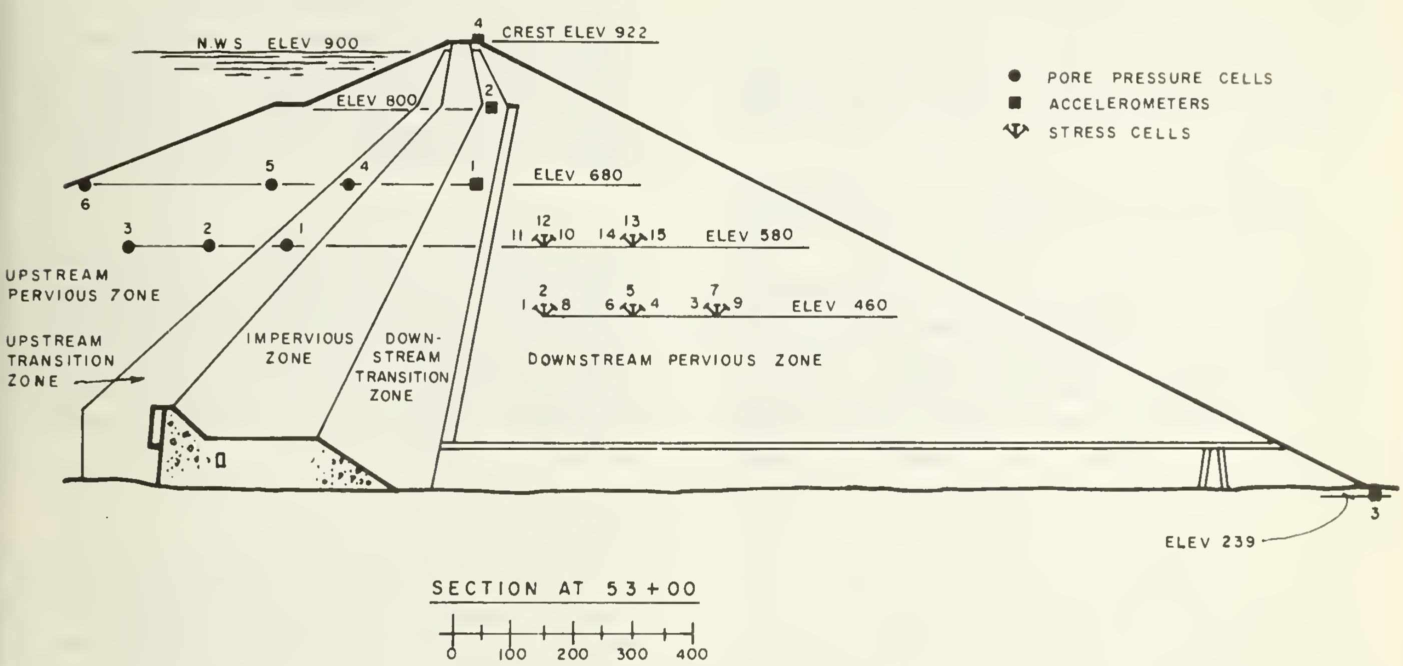

Figure 3. Oroville Dam Embankment Dynamic Instrumentation

The maximum increase in static pore pressures in the impervious zone induced by the first day shocks was approximately 44 feet (13.41 m). Subsequent aftershocks increased the pore pressure an additional 12 feet (3.66 m) giving a total maximum pressure rise of 56 feet (17.07 m). Presently the reservoir is being lowered to accommodate flood reservation and the pore pressures are receding accordingly. The lower pressure only reflects the decrease in reservoir loading with the earthquake induced pore pressure decreasing very slowly. One piezometer in the upstream transition zone showed an increase of approximately 40 feet (12.2 m) and the dissipation has been slow. This slow dissipation of pressure is assumed to be attributable to finer grained materials which were probably placed around this instrument. This behavior and its explanation are substantiated by the fact that this instrument developed pore pressures during the construction of the dam.

The maximum rise in dynamic pore pressure in the upstream pervious zone was approximately 23 feet (7.01 m) and dissipated immediately. The maximum rise in dynamic stress cells was approximately 23 psi (1.62 kg/sqcm) and dissipated immediately.

No change in the seepage occurred at the toe of the dam; it has remained constant at 14 gpm (0.88 l/sec). A slight increase in the total quantity of seepage in the grout gallery was observed. Most of the increase was attributed to the right abutment area.

A minor downstream movement in a portion of the dam in the order of 0.06 feet (0.02 m) was measured by horizontal devices but no movement of the instrument house on the downstream berm was observed. Surface monuments on the crest above the impervious zone indicated about 0.35 inches (9 mm) of total vertical settlement of the crest. The crossarm device located in the downstream pervious zone indicated a settlement of 0.51 inch (13 mm) at the top of the device. It also showed a foundation settlement of approximately 0.24 inch (6 mm) at its base.

The Oroville Dam spillway (Figure 1) suffered no structural damage and will require no additional maintenance due to the earthquake. Some slight evidence of possible movement was observed, including some spalling of loose laitance type concrete.

Oroville Dam withstood the earthquake with no structural damage and no slides or sloughing occurred in the reservoir. The shaking due to the earthquake has probably increased the inherent strength of the dam through additional consolidation. The knowledge gained from the Oroville earthquake will be utilized to reevaluate DWR dams and facilities with respect to future earthquakes.

Edward Hyatt Powerplant and Switchyard

Edward Hyatt Powerplant (formerly called Oroville Powerplant) is an underground pumping-generating facility located in rock (Figure 4), in the left abutment near the axis of the dam. Following the earthquake, an inspection was made of the structure, mechanical and electrical equipment, rock cavern (roof), penstock entrances and the ceiling and truss system. No damage to any of the features was visible and no offsets or displacements of equipment or structure were seen

The 230 kV switchyard is located approximately 1,500 feet (457 m) southwest of the underground powerhouse near the portal of the access tunnel (Figure 1) Close inspection with the aid of field glasses did not reveal any structure or equipment damage or any cracks in the porcelain insulators.

Thermalito Diversion Dam

Thermalito Diversion Dam, a concrete gravity structure (Figure 5) diverts water into Thermalito Power Canal (Figure 1) for power generation at Thermalito Powerplant and creates a tailwater pool that acts as a forebay when Edward Hyatt Powerplant is pumping water back into Lake Oroville.

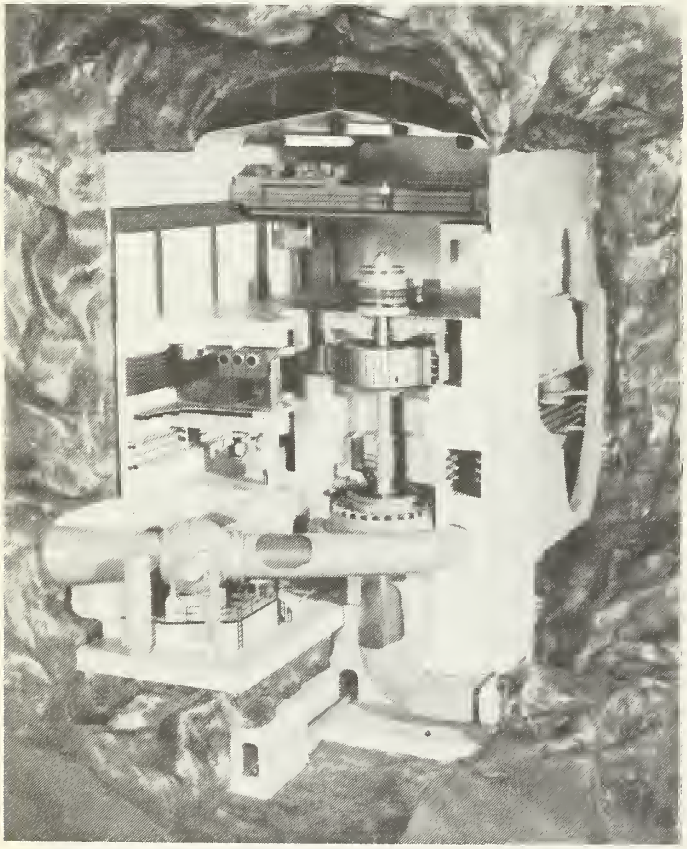

Figure 4. Edward Hyatt Powerplant (model)

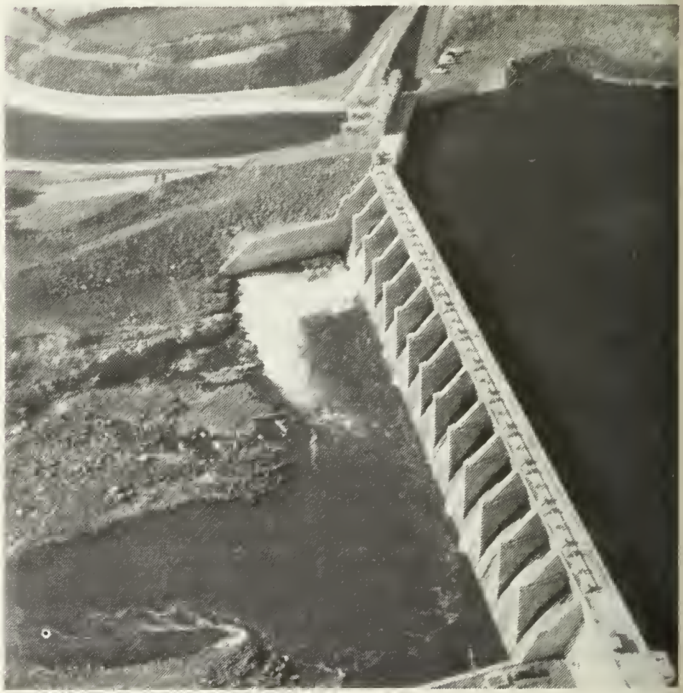

Figure 5. Thermalito Diversion Dam

No damage to the dam is evident and no offsets or movements of the structure or the 14 radial gates on the spillway crest occurred. The only noticeable change that occurred was the rate of seepage into the grout gallery. The seepage increased from 8.0 gpm (0.50 l/sec) to about 10 gpm (0.63 l/sec) which is a negligible seepage rate for this size of dam.

Thermalito Power Canal and Forebay

No sloughing, slides, or displacements occurred in the Thermalito Power Canal or the Thermalito Forebay (Figure 1). Inspections did not reveal any additional seepage or cracks in the canal lining.

Thermalito Powerplant and Switchyard

Thermalito Powerplant is an indoor-type with an inline arrangement of units and utilizes a massive reinforced concrete headworks with penstocks, penstock intakes and bypass (Figure 6). Located between the powerhouse and the headworks is the facility's switchyard. Immediately after the earthquake, an inspection was made of the structure, equipment, penstocks, headworks, approach channel dam, penstock connections to headworks and forebay slopes. No structural damage was visible except for some minor spalling of the plant superstructure's precast concrete panels approximately six to eight inches (15.2 cm to 20.3 cm) long. No offsets or displacements of equipment were visible and no sloughing of the slopes of the intake channel had occurred. No damage to any of the switchyard structures, equipment or porcelain insulators was visible.

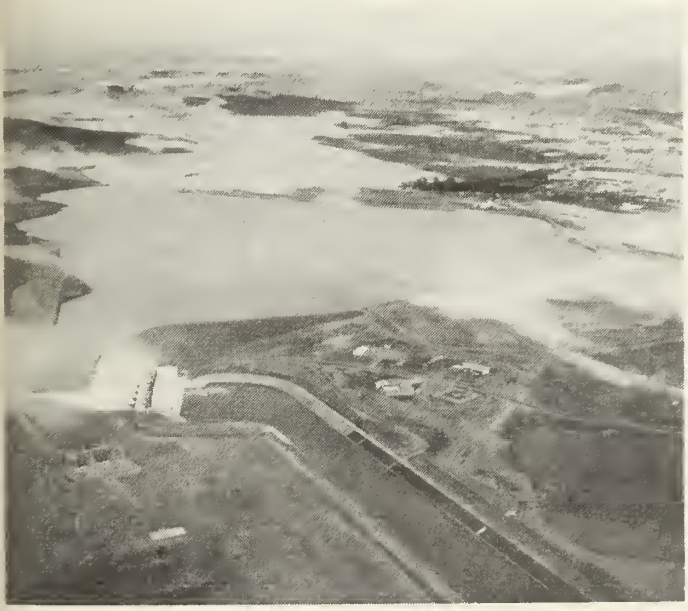

Figure 6. Thermalito Powerplant

Thermalito Afterbay and Tail Channel

The tail channel hydraulically connects Thermalito Powerplant with the Thermalito Afterbay (Figure 1). This channel is approximately 1-1/2 miles (2.4 km) long and was constructed with a 70-foot (21.3 m) bottom width and 2:1 side slopes. The channel section is lined with a 1-foot-thick layer of stone slope protection on a 6-inch (15.2 cm) layer of sand bedding. Considerable sloughing of riprap occurred at and below the water surface. The sloughing will not interfere with normal operations. Cracks paralleling the channel were observed between the water line and the crests of the roads adjacent to the channel. The movement appears to have occurred in the uncompacted sand bedding.

The Thermalito Afterbay Dam is approximately 6 miles (9.66 km) southwest of the City of Oroville (Figure 1) and contains the Thermalito Afterbay on the south and west sides while higher natural ground completes the containment on the north and east sides of the 57,041 acre-foot (70,360,000 m^3) reservoir.

An inspection of the entire afterbay indicated no damage except near the river outlet area (Figure 1). At the river outlet one longitudinal crack was evident in the embankment on each side of the outlet structure; the cracks were 30 feet (9.14 m) long and approximately 1/2-inch (1.27 cm) wide. The embankments between the river outlet and fish barrier weir at the Feather River (Figure 7) sustained the most damage from the shock. These embankments received lesser compaction than the dam during construction. Many longitudinal and some transverse cracks on the crest and slope of both sides of the channel are evident (Figure 7). Neither the river outlet or fish barrier weir sustained any apparent damage.

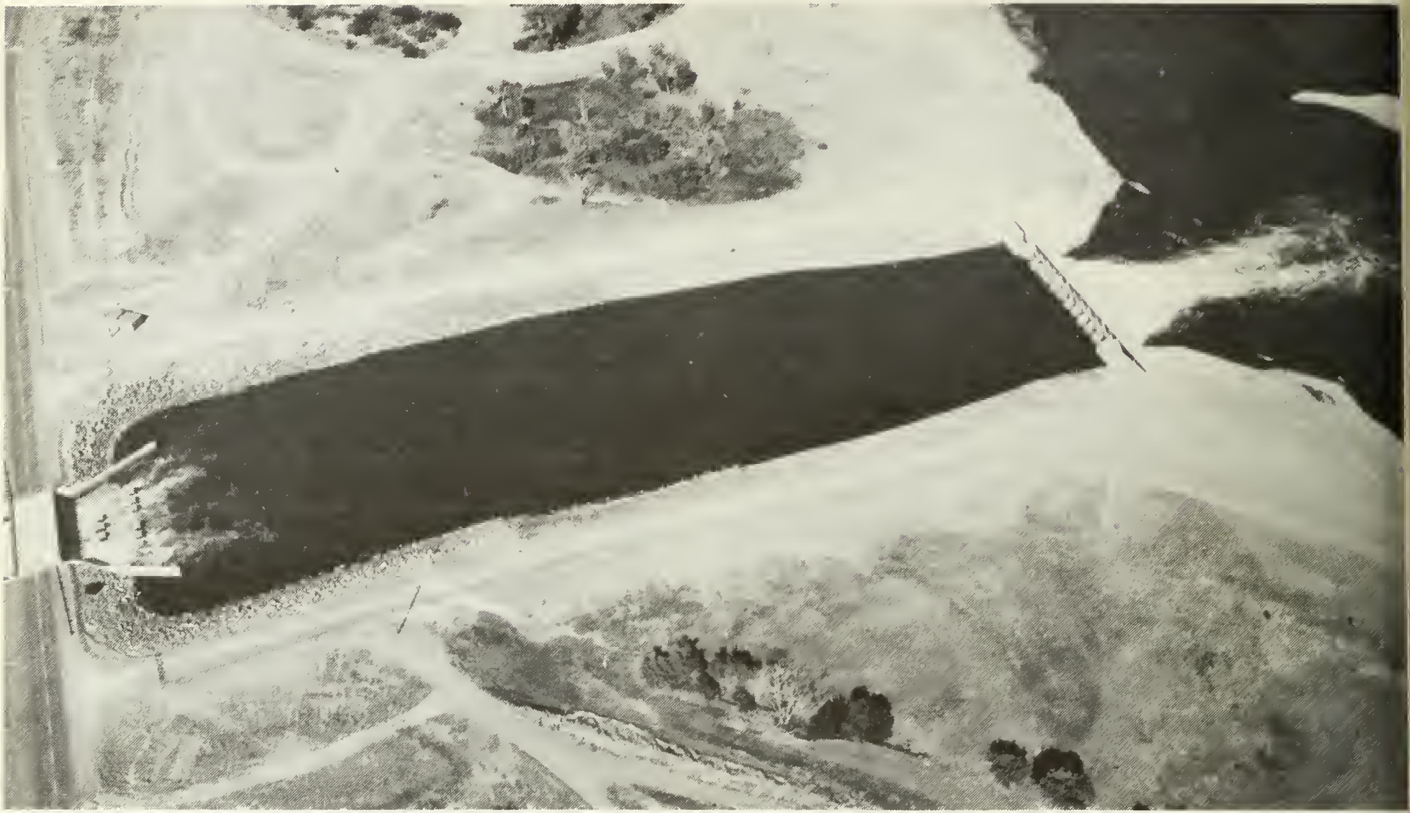

Figure 7. River Outlet and Fish Barrier Weir

Miscellaneous Structures

Some of the bridges in the area experienced some minor displacements and concrete spalls. None of the damage will require repair.

CONCLUSIONS

Even though the City of Oroville sustained much earthquake damage and was nearly declared a major disaster area by the President, Oroville State Water Project facilities shrugged off the effects of ground shaking with little or no damage. This final conclusion was reached after many exhaustive inspections by Department of Water Resources staff. However, the Department is undertaking detailed follow-up investigations taking advantage of the vast amount of accumulated seismic data to update existing seismic instrumentation at Oroville and other dams. Also the new data will be used to improve the state of the art of earthquake analyses.

ACKNOWLEDGEMENTS

Reviewed by Ernest C. James, Vernon H. Persson, Donald H. Babbitt and Henry E. Struckmeyer.

The author thanks Stephen H. Chan, Gerard A. Hayes, Ernest C. James, Herbert C. Johnson, Joey T. Ishihara, Phillip A. Law, James H. Lindgren, Samuel J. Linn, Jr., Vernon H. Persson, Marian Pona, and Wilford B. Shurtleff for use of their inspection trip notes.

A special thanks to John R. Campbell, Leroy Clayton, and Devere Davis for their helpful discussions on interpreting much of the instrumentation data and Dale E. Martfeld for editing.

DAMAGE TO BRIDGES

By James Gates
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California Department of Transportation

The Division of Structures of the California Department of Transportation performed engineering investigations of bridges in the Oroville area between August 5th and 6th, 1975. The field investigations were conducted by Mr. E. K. Hirst, Mr. P. Kin, Mr. B. E. Cochran, and Mr. H. C. Johnson of the Maintenance Engineering Branch. In addition, Mr. R. Taber of Moore & Taber investiaged Butte County Bridges. All bridges within an approximate ten mile radius of the epicentral region were investigated. At the request of Butte County, City of Oroville, and the Department of Water Resources, bridges under their jurisdiction were investigated in addition to State owned bridges. Of the 98 bridges examined, 78 were on the State Highway System, nine were on Butte County roadways, two on Oroville city streets, and nine were under the jurisdiction of the Department of Water Resources.

Evidence of movement and/or minor damage was noted at 14 bridges in the area:

State Bridges	3
County Bridges	6
City Bridges	2
Water Resources Bridges	3
Total	14

Figure 1 shows the location of the 14 bridges which showed evidence of significant movement and/or damage.

The only damage which will require repairs was limited to two State Highway bridges (Index 1 and 2 on map). The cost of these repairs is estimated to be $5,000.

ACKNOWLEDGEMENTS

Reviewed by A. F. Goldschmidt and R. W. Reynolds.

Table 1
Bridge Damage Data

MAP INDEX NO.	BRIDGE NO.	JURISDICTION	BRIDGE NAME	OBSERVATIONS
1	12-141 R/L	State	Feather River	Spalled bearing grout pad fillets. Cracks in retaining walls. Est. $1,000 repairs
2	12-34	State	Feather River	Spalled pedestals and curb at Pier 4. (Figure 2) Crack in fill at east abutment. Est. $4,000 repairs
3	12-31	State	Thermolito Afterbay	Cracks in Abutment 1.

Table 1 (Cont.)
Bridge Damage Data

MAP INDEX NO.	BRIDGE NO.	JURISDICTION	BRIDGE NAME	OBSERVATIONS
4	12C-200	County	Feather River	Approx. 5/8" movement of expansion bearings.
5	12C-231	County	Kusel Rd. OH	Possible tilt of abutment bearings of ¼". Minor approach pavement settlement.
6	12C-21	County	N. Honcut Cr.	Minor approach pavement settlement.
7	12C-365	County	Wilson Cr.	Minor approach pavement settlement.
8	12C-128	County	Wyandotte Cr.	Evidence of ¼" to 3/8" of circular movement and 1" settlement at pile bents and abutments (Figure 3).
9	12C-138	County	Wyandotte Cr.	Approx. ¼" movement and minor settlement.
10	12C-18	City	Oroville OH (Montgomery St.)	Minor settlement at westerly approach.
11	12C-01	City	Oroville OH (Bridge St.)	Minor sloughing of rock along wingwalls.
12	12C-258	Resources	Thermolito Canal	Approx. 1/8" displacement in Abutment 6 bearings.
13	12C-262	Resources	Lake Oroville Spillway	Top of north retaining wall moved inward approx. 2".
14	12C-229	Resources	River outlet (Larken Rd)	Small deck spall NE expansion armor.

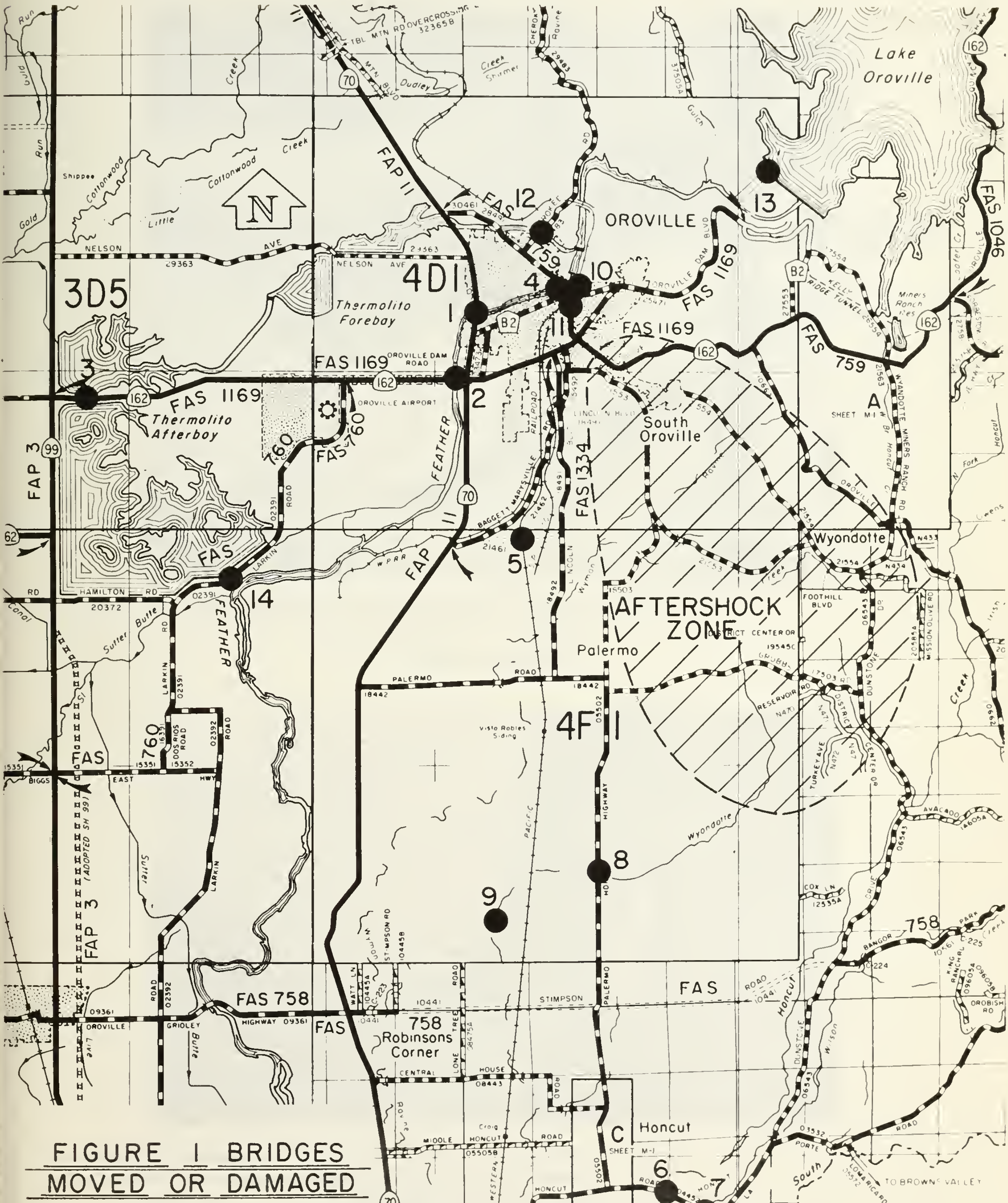

FIGURE 1 BRIDGES MOVED OR DAMAGED

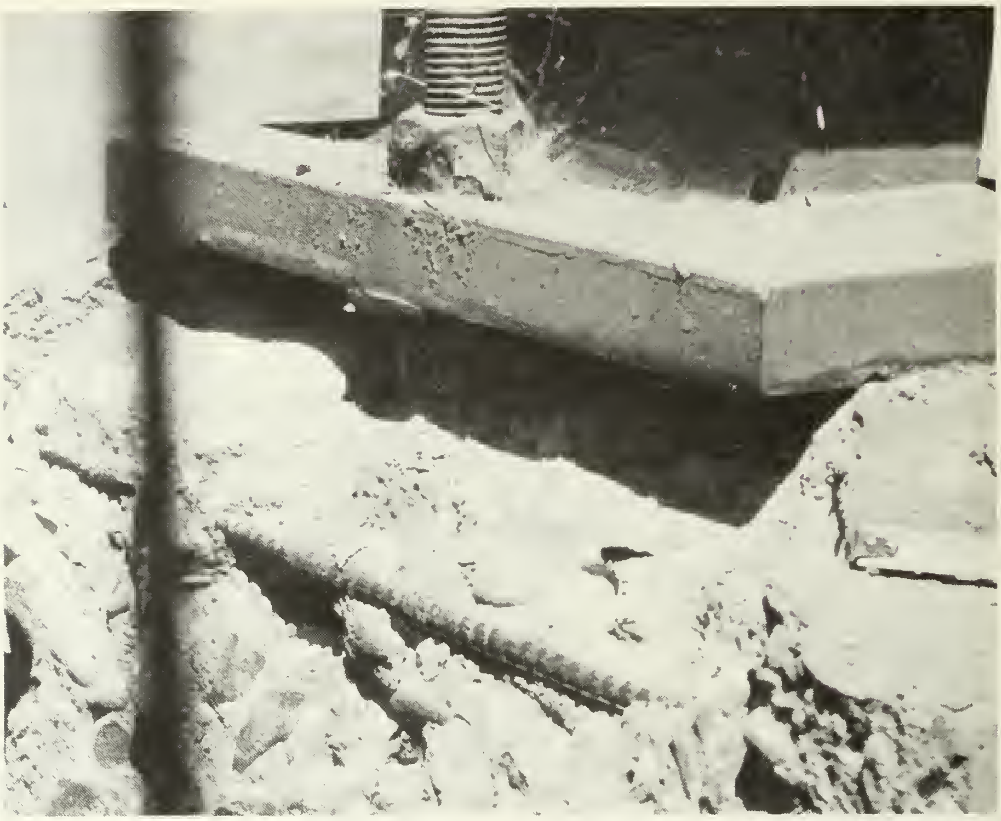

Figure 2 Anchor bolt damage at Feather River (Index 2, Bridge 12-34)

(CALTRANS Photo)

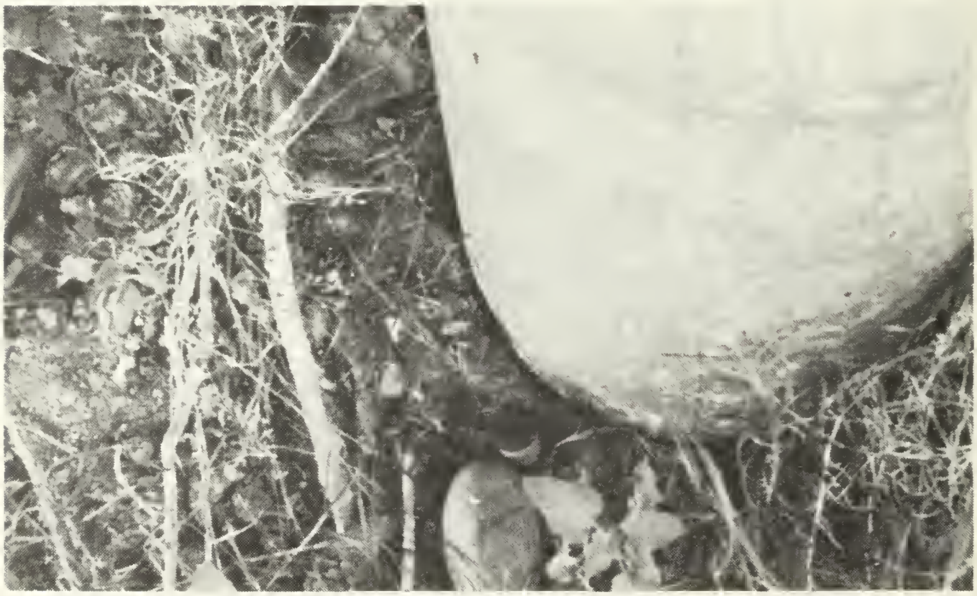

Figure 3 Evidence of pile movement at Wyandotte Creek (Index 8, Bridge 12C-128, County No. 229)

(Moore and Tabor Photo)

SECTION 4

SEISMOLOGY

PRELIMINARY REPORT ON THE FELT AREA AND INTENSITY

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INTRODUCTION

No major damage was reported from the Oroville earthquake, even though it was felt over most of central California and extreme western Nevada between 37° and 41° North latitude (Figure 1). The maximum intensity of VII was assigned only to the Oroville area (including Thermalito), where there were reports of 10 people injured and moderate property damage.

The epicenter was located by the University of California, Berkeley, at latitude 39° 26.33' North and 121° 31.71' West, about 9.5 kilometres (6 miles) south of Oroville, near the town of Palermo. The magnitude was computed at 5.7 M_L (Berkeley) and 5.9 m_b (USGS).

The contiguous felt area was approximately 120,000 square kilometres (46,320 square miles), but there were a few isolated felt reports in the San Francisco Bay area and in the region between Ukiah and Fortuna and west of the contoured felt area. In the Bay area it was reported felt at Oakland (III), Fremont (II), Menlo Park (II), Redwood City (II), Rodeo (II), and San Lorenzo (II); and in the region north of Ukiah, at Canyon (IV), Greenwood (IV), Rio Dell (III), Boonville (II), Casper (II), and Hayfork (II).

DAMAGE AND OTHER EFFECTS

Ten persons in the Oroville area were treated for minor injuries, mostly cuts from flying glass, and several people were treated for hysteria or suspected heart attacks.

Preliminary damage reports from Oroville were mostly of broken and shattered windows, including plate-glass windows in downtown stores; plaster and ceiling tiles broken and fallen; cracks in walls; and goods knocked from shelves. Outdoors there were small landslides; chimneys had been cracked and twisted, and some had fallen; and small fires were caused by downed power lines. Several buildings were temporarily evacuated following the earthquake, including the Butte County Courthouse which was reported to have suffered some structural damage.

In the Intensity VI zone, slight damage was reported in some wood, brick, and concrete-block structures. At Berry Creek, the old Post Office building, which was partially built on "stilts," shifted from the pre-earthquake position and suffered slight damage.

The effect of the earthquake at the Mathews Ready Mix Plant, located about 8 kilometres (5 miles) southwest of Oroville, was as follows (taken from a report by Dan N. Tidwell, Lowry and Associates, Geotechnical Engineers): "At approximately 1:20 p.m., I had just sat down in my truck to have lunch. My first indication was a distant 'roar' perhaps like the rumble of a train. The shaking started within a few seconds and seemed to increase slowly after a few seconds of relatively minor movement. At this time, I made the decision to move away quickly from the plant. The door of the truck was open so I started running diagonally away from the plant. I ran approximately 50 yards and stopped and looked back at the plant. At this time, the major shaking was still going on and the entire earth and plant and auxiliary buildings appeared to be moving up and down ±6". The feeling was one of being on a giant rock crusher, very severe and very rapid, perhaps ten cycles per second. There was a lot of noise, both from the equipment shaking and the surrounding stockpiled materials settling and also a background roar of the quake itself. I would estimate the major motion lasted less than 30 seconds. In the minutes after the quake, I stayed in one place and could feel the earth 'quiver' as if resonating."

ISOSEISMAL MAP

The felt area on Figure 1 was mapped primarily from 640 "Earthquake Reports" returned from a canvass of postmasters taken by the National Earthquake Information Service. Included also is information from collaborators who live in the area affected by the earthquake. Intensities (Figure 1) were rated according to the Modified Mercalli Intensity Scale of 1931 (Wood and Neumann 1931).

Figure 1 contains the composite of intensity values resulting from the data received but only a representative distribution of the "not felt" reports. The isoseismals were not extended to include isolated intensities because of numerous not felt reports that separated these isolated points from the contiguous felt area.

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ACKNOWLEDGMENTS

Reviewed by James N. Taggart and William J. Spence.

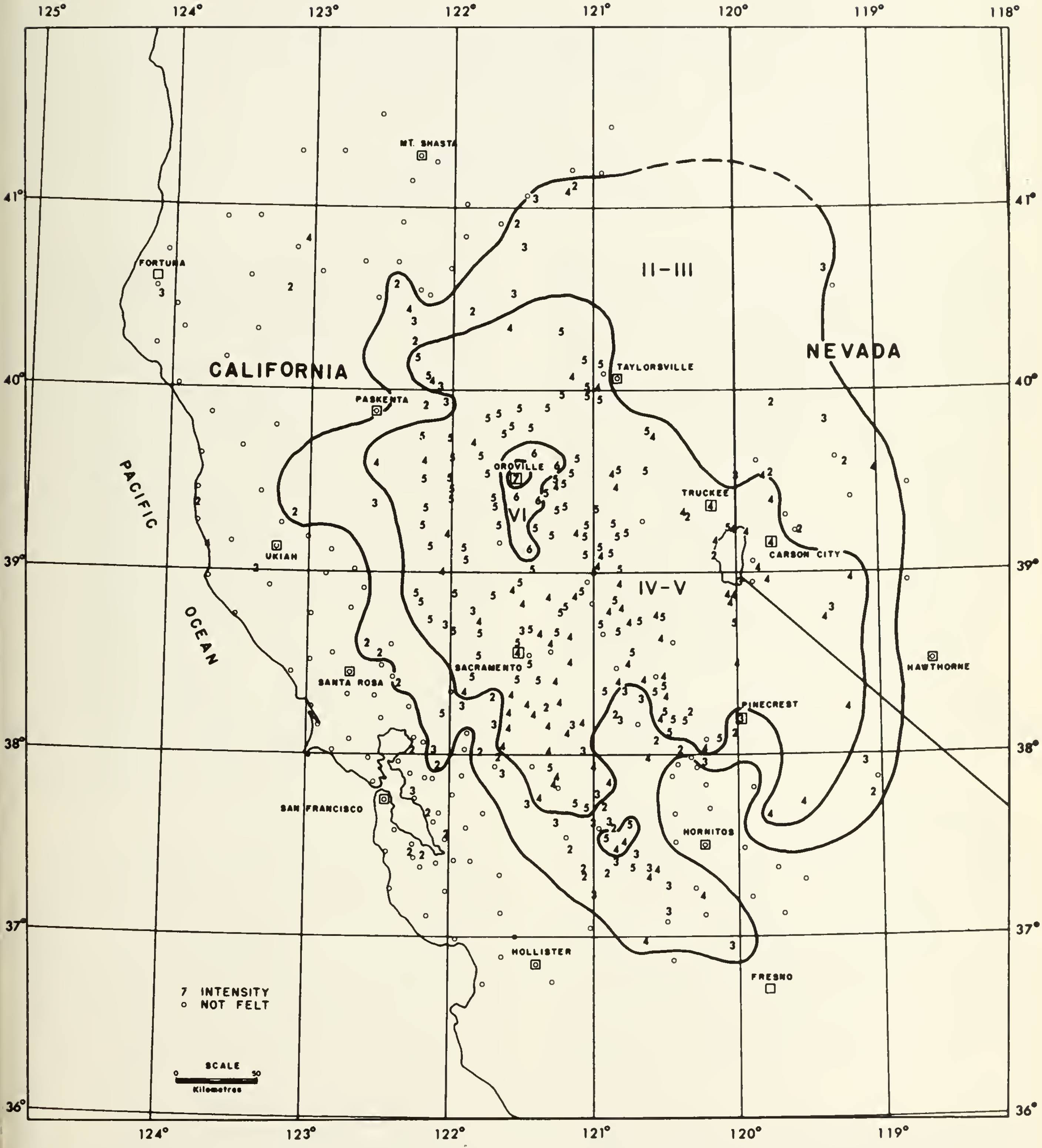

FIGURE 1. - PRELIMINARY ISOSEISMAL MAP OF THE OROVILLE EARTHQUAKE, AUGUST 1, 1975, 20:20:12.8 UTC

STRONG MOTION ACCELEROGRAMS
OF THE AFTERSHOCKS

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Within 48 hours of the mainshock, 10 strong motion accelerographs, with WWVB time code recording, were installed in the epicentral area. The California Division of Mines and Geology (CDMG) installed 5 instruments, and personnel of the California Institute of Technology and the U.S. Geological Survey installed 5 instruments. On 7 August, 2 of the CDMG instruments were moved eastward, closer to the aftershock locations, and on 9 August a sixth CDMG instrument was added to the network. On 21 August 2 additional CDMG instruments were installed approximately 10 km to the north and to the south of the aftershock zone. With the exception of the latter 2 instruments, Figure 1 shows the site locations and the generalized geology. The instrumental package is basically that described by Dielman et al. (1975), although recent developments have allowed the radio time circuitry to be housed within the accelerograph.

Table 1 summarizes the accelerograph location data and lists the total number of records positively associated with known earthquakes for each site through 21 August. As of the time of this writing (14 October) the network is still operating in the field. The network recorded 123 accelerograms for 27 aftershocks of $M_L \geq 3.0$ through 21 August. Table 2 lists the hypocenters, magnitudes, number of positively identified accelerograms, and maximum horizontal acceleration for these 27 aftershocks. The large peak accelerations generated near the epicenters of many of the aftershocks are significant; particularly 19% g for $M_L = 3.2$ on 5 August and 22% g for $M_L = 4.0$ on 16 August. The largest accelerations recorded were for the 2 aftershocks labelled II and III in Figure 1. These events occurred on 6 and 11 August, and produced peak accelerations of 70% g and 43% g at station DJR and station 6, respectively, as indicated in Table 2. The accelerograms for these 2 events are displayed in order of increasing hypocentral distance in Figures 2 and 3. The uniform frequency of the station DWR accelerograms in Figures 2 and 3 is characteristic of all records obtained at this site, and suggests the presence of structural vibration. Consequently, peak values at DWR were excluded in compiling the maximum accelerations in Table 2. The DWR structure is an open steel-frame garage, approximately 50'x200' in area and 20' high, with masonry-enclosed storage areas at both ends.

The data set is remarkably complete for aftershocks of $M_L \geq 3.0$. From 20:59 on 2 August through 21 August, at least 1 strong motion accelerogram was obtained for every aftershock of $M_L \geq 3.0$. In this same interval, approximately 50 additional positively identified accelerograms were obtained for aftershocks of $M_L < 3.0$. Of particular interest were peak accelerations of 10% g for $M_L = 2.5$ at 9:13 on 5 August, and 5% g for $M_L = 1.8$ at 07:29 on 4 August.

This data set is significant because a large number of accelerograms were obtained for many aftershocks across a relatively broad magnitude range

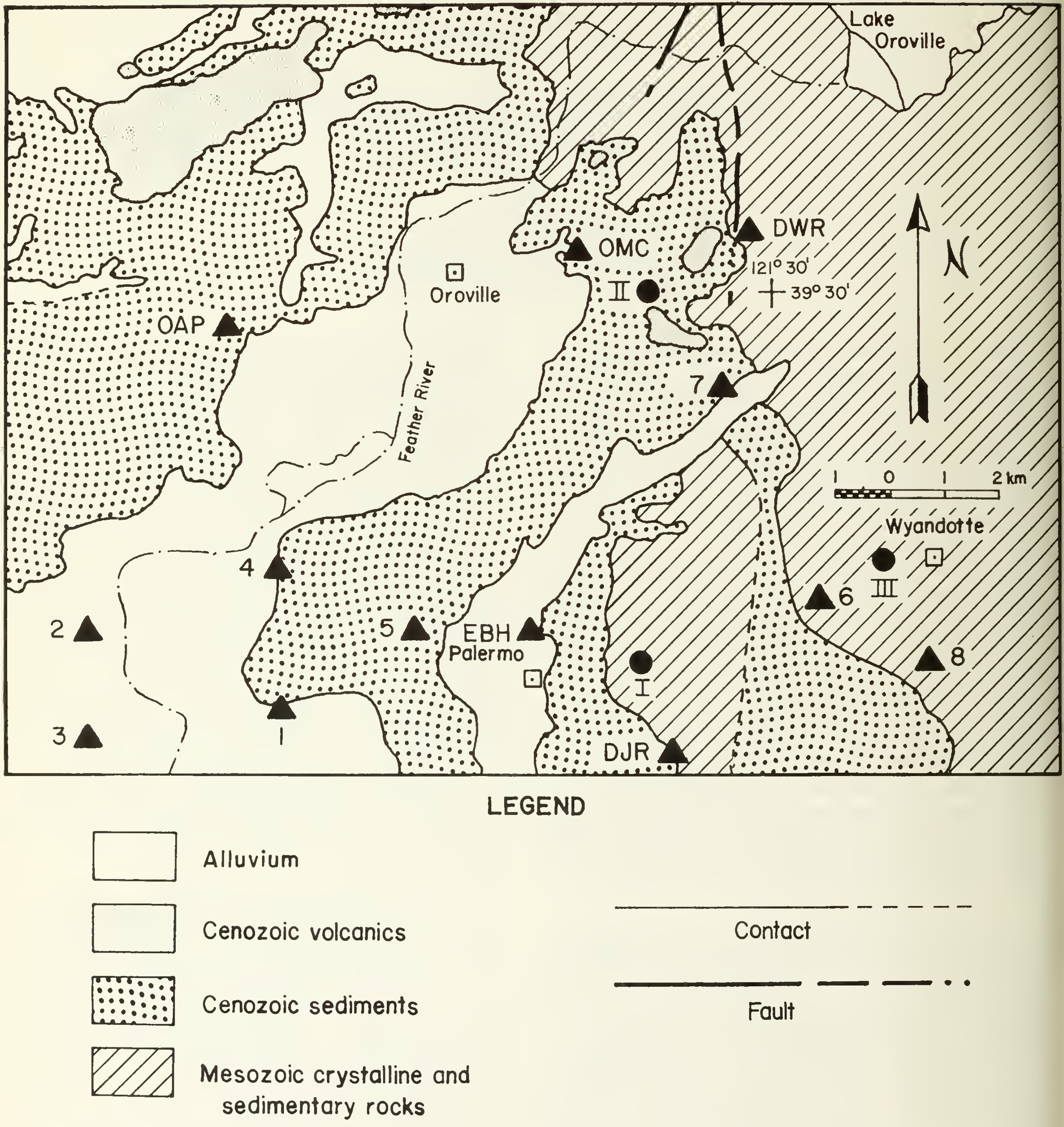

Figure 1. Location map showing generalized geology. Triangles are accelerograph sites identified as in Table 1. Circles are epicenters of earthquakes occurring in August 1975, as follows: I, mainshock 20:20 on 1st, M = 5.7; II, 03:50 on 6th, M - 4.7; III, 06:11 on 11th, M = 4.3.

TABLE 1 - Strong Motion Accelerograph Location Data

Sta.	Operator	Instal. Date August 1975 Day	Hour (GMT)	Lat. 39°N	Long. 121°W	Elev.	Number of Records Through August 21	L(a)	Type of Structure(b)	Site Geology
1	CDMG(c)	1	2100	25.95'	36.23'	125'	20	East	Wood frame	Recent alluvium
2	CDMG	1(d)	2300	26.75'	38.58'	115'	0(e)	West	Galvanized barn	Recent alluvium
3	CDMG	2(d)	1700	25.70'	38.53'	110'	8	N85W	Wood frame	Recent alluvium
OAP	CIT(f)	2	1900	29.75'	36.81'	190'	13	West	Steel frame	Cenozoic sediments
OMC	CIT	2	2100	30.42'	32.43'	260'	8(g)	North	Wood frame	Cenozoic sediments
4	CDMG	2	2100	27.35'	36.18'	167'	12	N35W	Wood frame	Cenozoic sediments
DWR	CIT	2	2300	30.60'	30.28'	410'	11	South	Steel frame garage	Mesozoic greenstone
EBH	CIT	3	0100	26.74'	33.00'	170'	18	East	Wood frame	Recent alluvium
5	CDMG	3	0100	26.70'	34.45'	190'	24	South	Wood frame	Cenozoic sediments
DJR	CIT	3	2000	25.47'	31.26'	240'	29	East	Wood frame	Greenstone - sediment contact(h)
6	CDMG	7	2100	26.93'	29.38'	550'	16	S55E	Concrete block 10'x 10'	Mesozoic greenstone
7	CDMG	7	2000	29.05'	30.60'	340'	12	West	Wood frame	Cenozoic sediments
8	CDMG	9	1700	26.35'	28.03'	600'	8	West	Wood frame	Mesozoic greenstone
9	CDMG	21	1800	20.13'	29.03'	250'	0	N20W	Adobe brick	Mesozoic greenstone
10	CDMG	21	2200	36.47'	31.65'	1400'	0	S20E	Wood frame	Mesozoic greenstone

(a) Pendulum motion for upward deflection of L Trace
(b) All structures are one-story except No. 10, which is two-story.
(c) California Division of Mines and Geology
(d) Removed 1730, August 7, 1975
(e) No WWVB time
(f) California Institute of Technology
(g) Poor WWVB time
(h) Greenstone 10 meters below surface

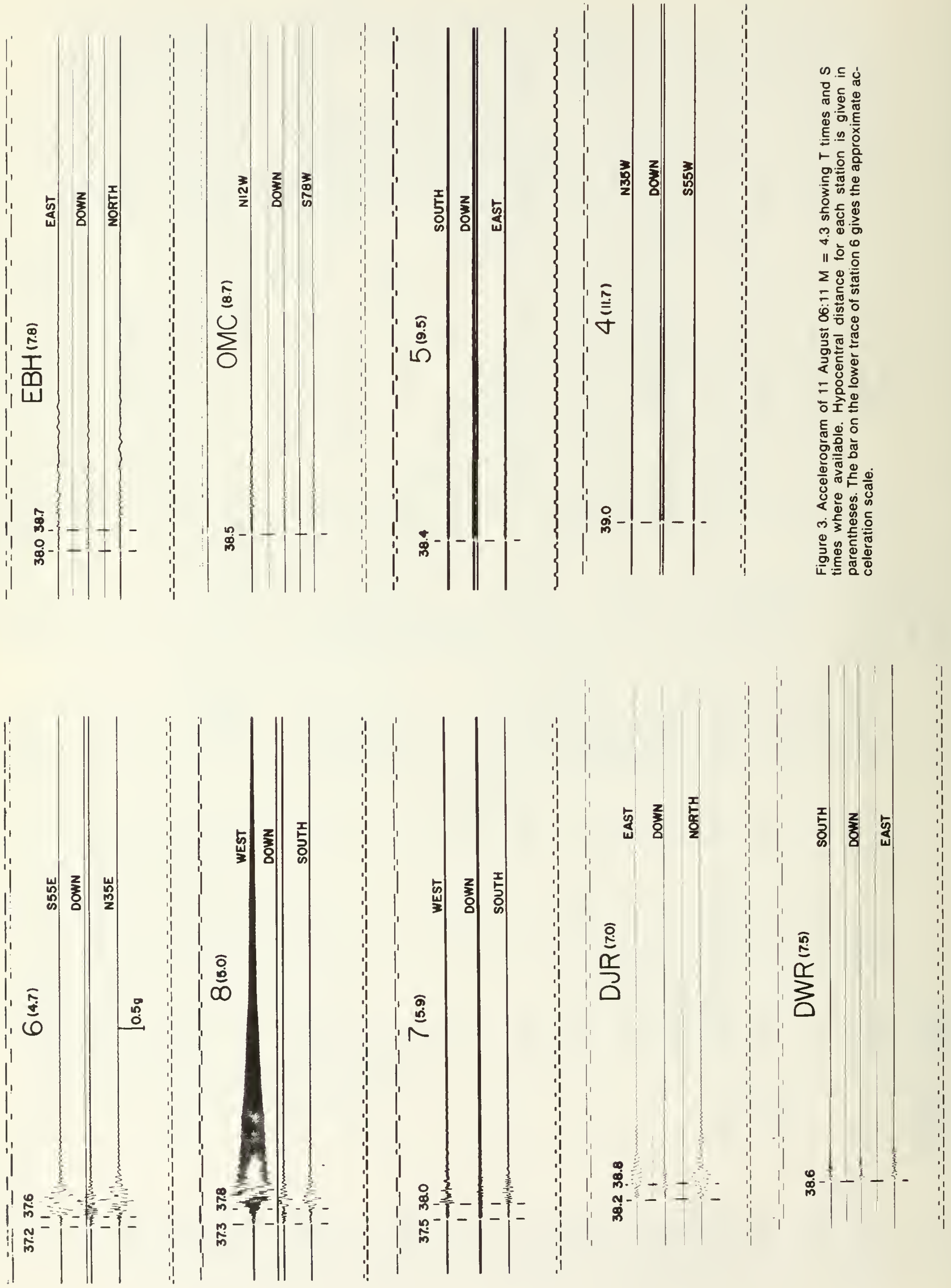

Figure 3. Accelerogram of 11 August 06:11 $M = 4.3$ showing T times and S times where available. Hypocentral distance for each station is given in parentheses. The bar on the lower trace of station 6 gives the approximate acceleration scale.

TABLE 2. Earthquake Source and Maximum Acceleration Data, $M_L \geq 3.0$
August 2 to August 21$^{(a)}$

Date	Origin Time						Number	Max. Accel.		Hypo-
Aug. 1975	Hr-Min	Sec	Lat. 39°N	Long. 121°W	Depth Km	M_L (b)	of Records	%g	Station	central Distance Km
2	0052	48.5	29.06'	30.55'	7.3	3.8	1	5	1	12.3
2	1151	50.7	28.36'	29.30'	2.5	3.4	1	4	1	11.2
2	1444	38.7	25.03'	29.38'	5.0	3.1	1	4	1	11.2
2	1651	45.1	25.07'	29.09'	6.5	3.7	1	4	1	12.2
2	1958	36.9	26.89'	32.20'	7.1	3.1	2	4	3	11.7
2	2022	16.3	26.69'	27.76'	3.6	5.1	2	5	OAP	14.6
2	2059		25.93'	27.97'		5.2	4	8	OMC	
2	2140	01.3	25.62'	28.39'	5.4	3.9	1	5	4	12.8
3	0103	05.8	29.26'	31.06'	8.0	4.6	8	18	EBH,OMC	9.7,8.5
3	0247	08.8	28.68'	30.06'	6.8	4.1	7	16	EBH	8.8
4	0947	45.0	25.27'	31.36'	7.6	3.5	5	11	DJR	7.6
5	0228	56.9	24.47'	29.55'	7.5	3.3	4	19	DJR	8.1
5	2044	24.3	26.44'	31.81'	9.2	3.2	5	19	DJR	9.4
6	0350	29.7	29.95'	31.53'	10.4	4.7	9	70	DJR	13.3
6	1625	46.9	24.29'	29.16'	8.4	3.1	3	10	DJR	9.2
6	1641	51.9	29.50'	31.45'	8.5	3.6	7	16	DJR	11.3
6	2100	32.8	24.90'	30.95'	9.6	3.0	2	3	1	12.4
7	2031	19.8	30.20'	31.34'	10.4	3.1	2	7	DJR	13.6
8	0700	50.6	29.92'	30.10'	6.8	4.9	9	21	DJR	10.8
8	1337	54.5	29.73'	29.33'	3.4	3.2	7	10	7	4.1
8	1903	28.0	24.56'	29.26'	5.0	3.1	5	9	EBH	8.4
9	0738	47.2	24.45'	29.55'	4.3	3.0	2	10	DJR	5.3
11	0240	16.5	27.80'	28.25'	1.5	3.0	3	6	6	2.7
11	0611	36.3	27.57'	28.65'	4.4	4.3	9	43	6	4.7
11	1559	05.6	30.31'	31.04'	8.7	3.6	11	11	DJR	12.4
12	1158	52.0	27.22'	30.12'	1.0	3.0	1	4	6	7.3
16	0548	09.1	28.37'	30.96'	9.4	4.0	11	22	DJR	10.8

(a) Hypocenters from August 2 to August 4 are U.C. Berkeley data; Hypocenters from August 5 to August 16 are USGS data.

(b) Berkeley Local Magnitude

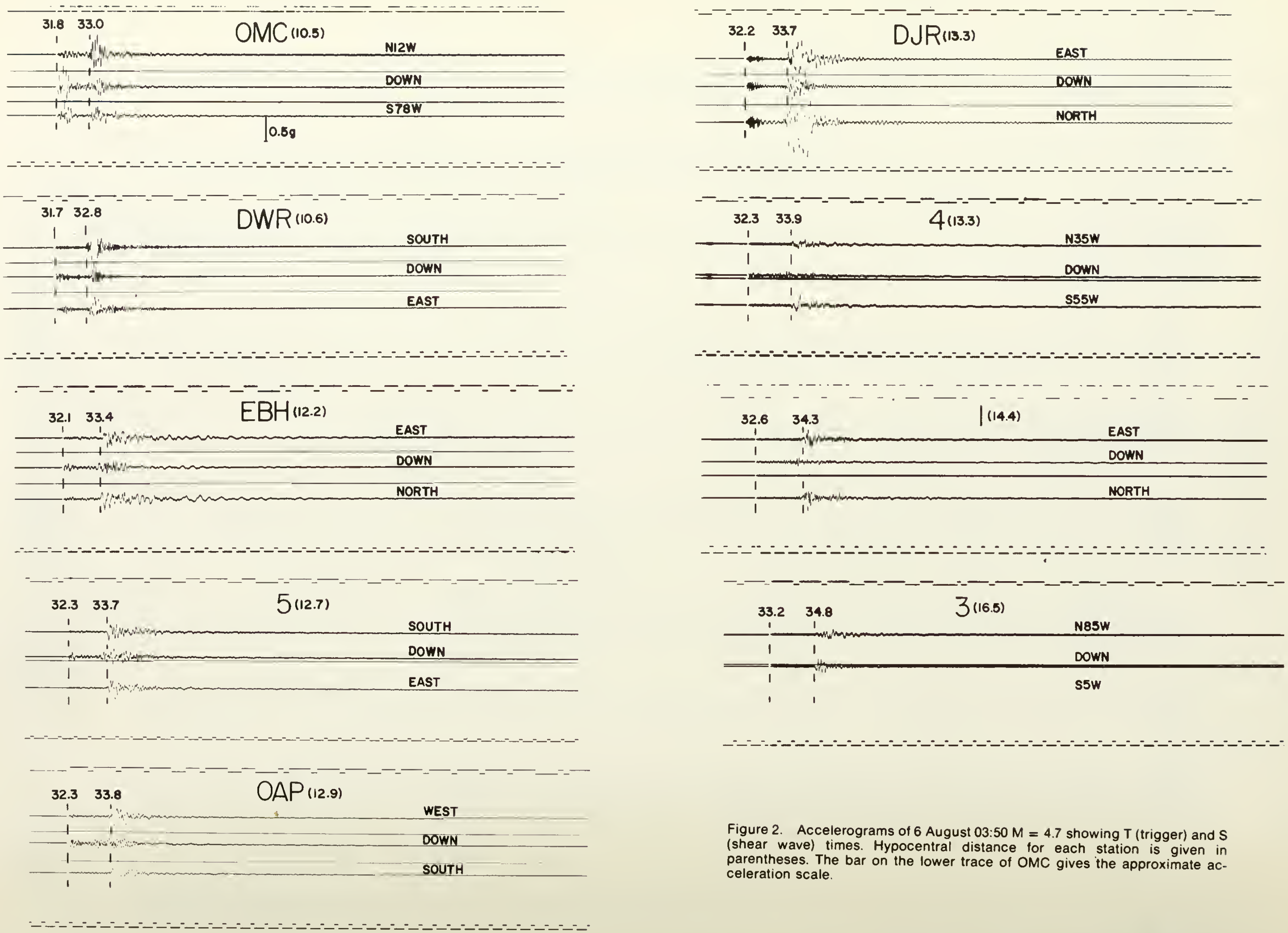

Figure 2. Accelerograms of 6 August 03:50 M = 4.7 showing T (trigger) and S (shear wave) times. Hypocentral distance for each station is given in parentheses. The bar on the lower trace of OMC gives the approximate acceleration scale.

($1.8 \leq M_L \leq 5.2$) at small distances. As was suggested previously on the basis of similar data presented by Dielman et al. (1975) and Johnson and Hanks (1975), the Oroville aftershock accelerograms clearly demonstrate the ability of strong motion accelerographs with absolute time capability to provide near field ground motion data of both engineering and seismological significance for earthquakes with magnitude as small as 3.

ACKNOWLEDGEMENTS

Raul Relles of CIT and Russ Forshee and Leroy Foote of the USGS installed, and maintained the CIT instruments. Harry La Gesse of CDMG installed and maintained the CDMG instruments. Kevin Donihoo and David Parke of CDMG participated in various aspects of this investigation.

The interest and patience of numerous residents of the Oroville-Palermo area facilitated rapid deployment of the instruments. For the CDMG instruments we thank Mrs. Armstrong (#1), Mr. Graves (#2), Mrs. Pierce (#3), Mr. Bruce Bausell (#4), Mrs. Mary Duffy (#5), Mrs. Hope Combes (#6), Mr. Harvey Nelson (#7), Mr. Jay Grubbs (#8), Mrs. Joie Osgood (#9), and Mr. Bob Bremer (#10). For the CIT instruments we thank Mr. Gover Wing (OAP), Mr. Earl Broadbeck (EBH), Mr. Don Johnson (DJR) and several members of the staffs of the Oroville Medical Center (OMC) and Department of Water Resources Civil Maintenance Section (DWR).

Reviewed by John T. Alfors and Roger W. Sherburne.

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SPECTRAL INVESTIGATIONS OF THE 01 AUGUST, 1975 OROVILLE EARTHQUAKE SEQUENCE

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In this paper we discuss wideband seismic data taken at close-in (5-15 km) and near-regional (150-175 km) distances from the 01 August 1975 Oroville earthquake and its aftershocks. Displacement spectra are computed and discussed.

The Data

A. Close-in Data

1. Field set-up--Four sets of 3-component SMA-2 event-recording accelerometer systems were deployed from 08 to 20 August, 1975. These devices trigger on .1% g and record the data on analog magnetic tape. In addition, wideband velocity data (1-20Hz) were recorded continuously from 02 August, 2300 GCT to 20 August. However, the gains were set high for hypocenter determination, so that only small events were on scale. These all appear to have significant energy above the pass band of these systems. Station deployment is shown in Figure 2 of Ryall and Van Wormer (1975), this volume.

2. Data collected--Fifteen sets of three-component accelerograms were obtained, of which 9 (27 spectra) were subjected to Fourier analysis. These include only the S-phase (no P at all).

B. Near-regional Data

The University of California at Berkeley operates three wideband systems, located at Whiskeytown (WDC), Berkeley (BRK) and Jamestown (JAS), 150 km NW, 175 km SW, and 175 km SSE, respectively, of Oroville. These are flat in velocity from .025 or .033 to 10 Hz. Also included at JAS and WDC are displacement systems recorded at two gain levels (46 db separation), which are flat in displacement from .025 to 10 Hz. These data are recorded continuously on analog magnetic tape, so that all the Oroville aftershocks above M_L ca. 2.5 are available. Only the BRK records of the main shock are missing.

Spectral Analysis

A. Close-in Data

1. Processing--The accelerograms were digitized (after 40-Hz alias filtering) at 167 samples per second. A 5% cosine taper was applied and a parabolic trend removed by least squares. Spectral moduli were computed, smoothed (three-point triangle window) and the system response (flat in acceleration to 17 Hz, flat in displacement 20-50 Hz) was removed. The instrument response curve was verified by a shake table test. Identical processing was performed on a noise sample.

2. Results--Unfortunately, no time code was recorded along with the events. We have so far been able to identify with certainty only two events, those of 11 August, 0611 GCT (up to 9 accelerograms), and 16 August, 0548 GCT (3 accelerograms). However, the unidentified events have provided one significant observation; almost all 27 spectra show corner frequencies in the 10-20 Hz range (the two exceptions are records of the 11 August 0611 event, the largest to occur during the time the instruments were deployed). A composite spectrum, with units chosen for convenience of plotting, is given in Figure 1. These corner frequencies are fairly high for earthquakes in the magnitude range 3-4.3 (Tucker and Brune, 1975). Spectral data for the two identified events is given in Table 1.

B. Berkeley Data

1. Processing--The records were digitized (after 10-Hz alias filtering) at 40 samples per second. A 5% cosine taper was applied and the mean removed. Spectral moduli were computed, smoothed as above, and the instrument response removed. Note that no Q-correction was applied (see below). Identical processing was

performed on a noise sample.

2. Results--(a) long-period spectrum. P-wave spectra of the mainshock were computed at WDC and JAS (the S-phase was too close to the large surface waves, which would have distorted any spectrum of this phase computed). These give excellent, flat spectra from 50 seconds to .1 or .2 Hz, a factor of ten or more above the noise. Using Hanks and Wyss (1972), these spectra give a seismic moment of $2x10^{24}$ dyne-cm from the long-period spectral level. The spectral data so far computed are presented in Table 1. Spectral data of the 16 August 0548 event are particularly excellent. They give 3 estimates of the seismic moment (Brune, 1970 or Hanks and Wyss, 1972) at BRK and WDC of $1.35x10^{21} \pm .3$ dyne-cm. This agrees fairly well with the close-in moment for the same event of $4.4x10^{21}$ dyne-cm. Close-in and near regional S-wave data for this event are shown in Figure 2.

(b) corner frequency data. One striking result is the great discrepancy between the S-wave corner frequencies of the 16 August 0548 event as measured by the close-in and near-regional data (10-11 Hz for the former, 1-1.7 Hz for the latter). Since the long-period levels of these spectra are roughly similar (when normalized for epicentral distance) we can safely assume that attenuation is responsible for the near-regional corner frequencies. We have fit the data by templates with the attenuation function exp (-3.1ft/Q) for various values of Q, where "f" is frequency (Hz), "t" is travel time, and "Q" is the anelastic attenuation factor. The appropriate value of Q (assuming that the "real" spectrum continues on flat to 10 Hz as indicated by the close-in data) is 300. This is quite high for S-waves as compared to other studies in Central California (Bakun and Bufe, 1975; Kurita, 1975; $Q \leq 100$).

The Oroville mainshock gave excellent P-spectra at JAS and WDC, with .1 to .2 Hz corner frequencies. Madariaga's (1975) theory would give (for a circular fault) a source radius of 6-12 km, which is in line with the size of the aftershock zone. These data are given in Figure 3.

The 02 August 2053 GCT aftershock ($M_L = 5.1$) gives excellent data which are puzzling in terms of source theory. JAS gives a P-spectral corner frequency of .2 Hz followed by slow decay (as 1/f) to 3 Hz; the WDC S gives a strongly peaked spectrum in the .5 to .7 Hz band; the BRK P and S give excellent but totally different spectra (.1 Hz corner for P, 1.0 Hz corner for S; see Figure 4). The low P-corner frequencies suggest a source dimension for this event similar to the Oroville mainshock (i.e. 12-24 km); they are probably not caused by attenuation.

Significance of these Results

We have seen in Figure 1 that corner frequencies of the Oroville events are quite high compared to other Western U. S. earthquakes of comparable magnitude. We notice also in Table 1 that the moments for these events are fairly low compared to Wyss and Brune's (1968) plot of moment versus magnitude. This suggests that it may be possible to develop a spectral discriminant for Oroville earthquakes. An important seismological point to resolve (if possible) is whether loading by the Oroville reservoir triggered the Oroville earthquakes. The existence of a spectral discriminant for these events would be provocative and germane to this point. However, Peppin and McEvilly (1974) computed moments for Nevada Test Site events known to be induced by explosions. Their results show that these earthquakes are normal compared with other Western U. S. events. Thus, we can only conclude that the anomalous spectral data of the Oroville sequence is due to some combination of peculiarities of that area, possibly (but not necessarily) including the influence of rapid reservoir filling.

In any case, we have confirmed that moments computed in the near field essentially agree with those found from near-regional data for this sequence.

ACKNOWLEDGMENTS

Professor McEvilly kindly provided data recorded by the University of California, Berkeley long period array. This work was supported by AFOSR Grant F44620-72-C-0069.

The manuscript was reviewed by A. Ryall and D. VanWormer.

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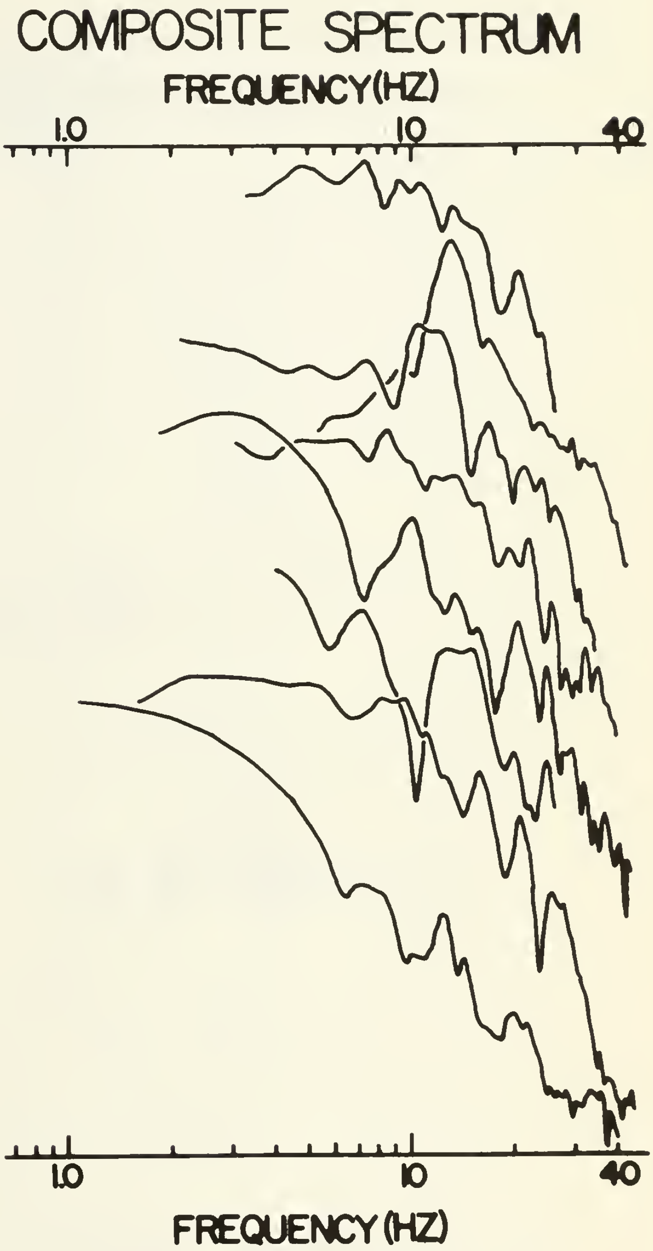

Figure 1: Some of the better of 27 close-in spectra obtained from a dozen events. Spectra are shown where signal-to-noise ratio exceeds a factor of 2. Ordinate chosen for plotting convenience.

Table 1

Event	Phase	Station	Inst(1) Type	Mo(2) (dyne-cm)	fc(2)(4) (Hz)
Oroville M/S	PZ	WDC	D	1.63x10^{24}F	.1 F
Oroville M/S	PZ	JAS	D	2.40x10^{24}E	.2 E
02 Aug 2023	PZ	JAS	D	6.67x10^{22}E	.23 ?
02 Aug 2023	SH	BRK	V	1.77x10^{22}E	1.0 G
02 Aug 2023	PZ	BRK	V	5.11x10^{22}E	.12 E
02 Aug 2140	PZ	WDC	V	2.5 x10^{21}G	?
02 Aug 2140	PZ	JAS	D	3.9 x10^{21}G	?
11 Aug 0611	SV-SH	A3-1	A	1.4 x10^{22}G	4 E
11 Aug 0611	SV-SH	A3-2	A	6.8 x10^{22}E	2.3 E
11 Aug 0611(3)	SV-SH	A2-1	A	(1 x10^{21}E)	10 E
11 Aug 0611(3)	SV-SH	A4-1	A	(5 x10^{20}E)	9 E
16 Aug 0548	SH	BRK	V	1.6 x10^{21}	1.1 G
16 Aug 0548	PZ	WDC	V	1.5 x10^{21}	1.0 G
16 Aug 0548	SV-SH	WDC	D	9.5 x10^{20}	1.7 G
16 Aug 0548	SV-SH	A1-1	A	5.4 x10^{21}	10 E
16 Aug 0548	SV-SH	A1-2	A	3.2 x10^{21}	11 G

(1) D - displacement (.025-10Hz)
V - velocity (.025 or .033-10 Hz)
A - acceleration (to 17 Hz)

(2) quality E = ± 5%, G = ± 10%, F = > ± 10%, ? = uncertain

(3) identity of these records not certain

(4) corner frequency found by overlaying a template with flat part at long period and decay as f^2 or f^3 to high frequency.

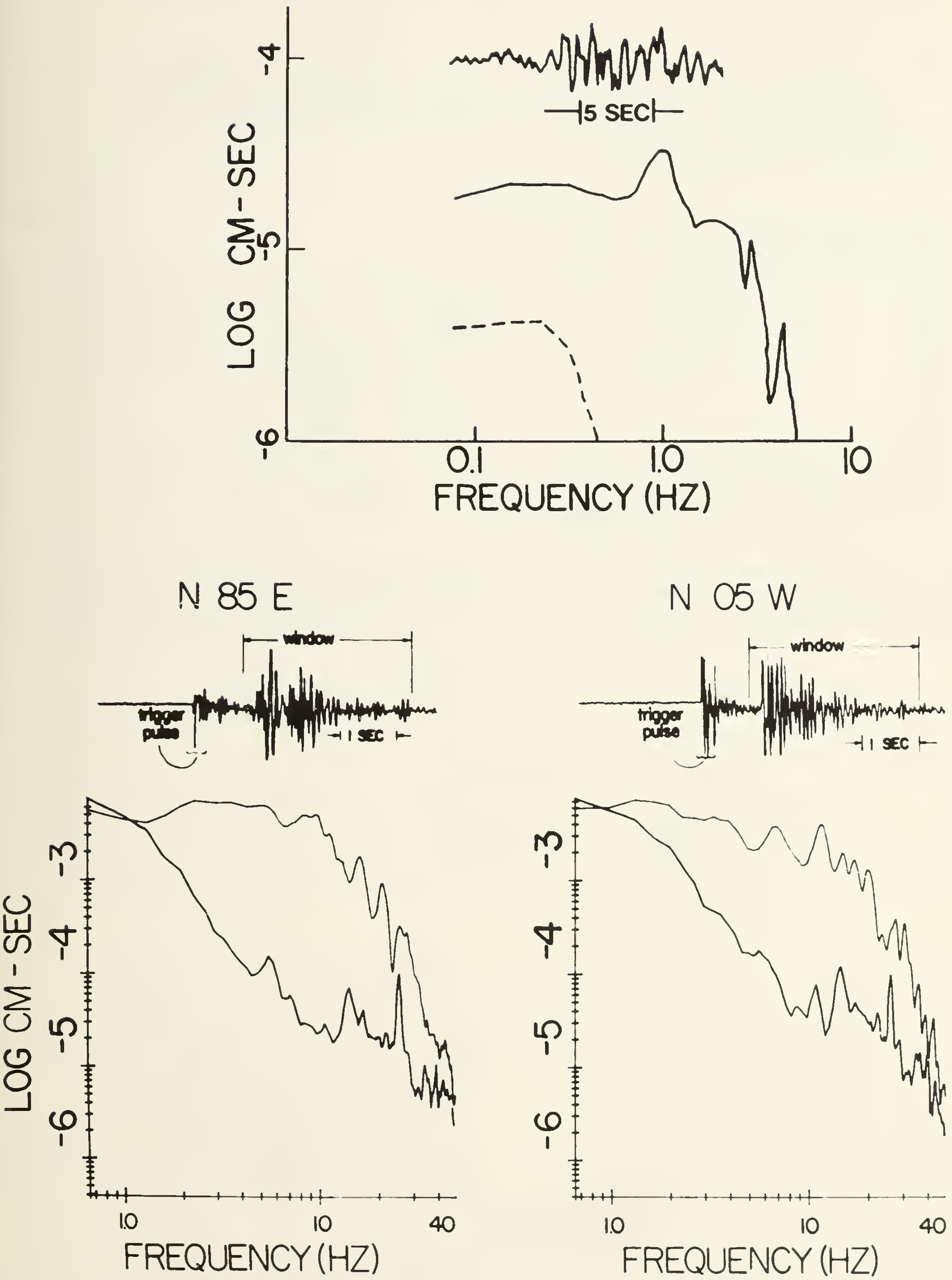

Figure 2. The 16 August, 0548 GCT event. Top: SZ as recorded on displacement system at WDC. Bottom: two horizontal components of acceleration as recorded a few km from the epicenter at station HMK (Ryall and VanWormer, 1975, this volume, Figure 2). The lower trace on each spectrum is an estimate of the noise (see text).

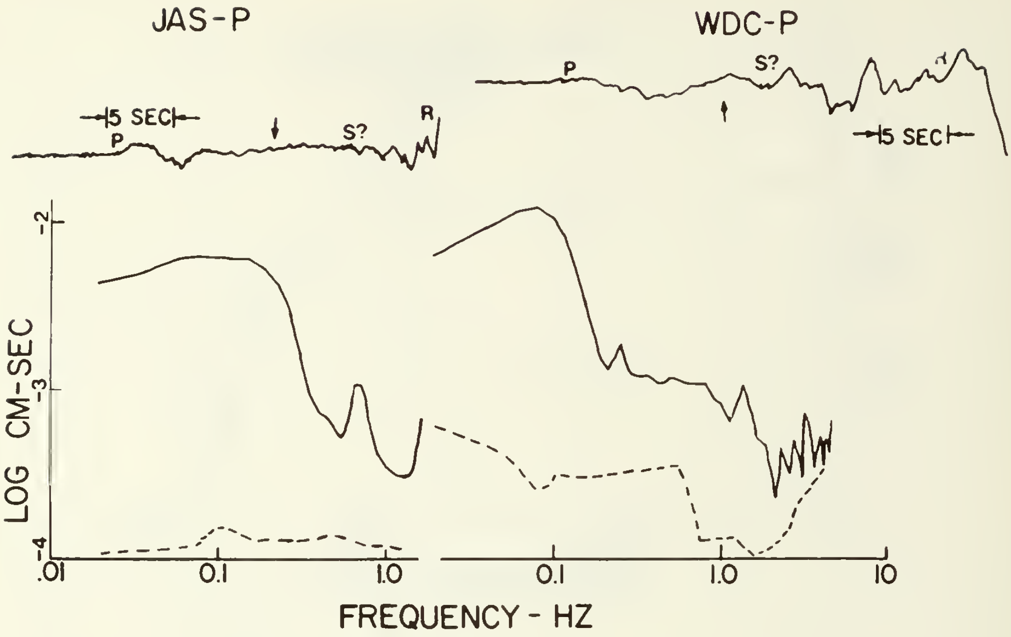

Figure 3. The Oroville mainshock as recorded by displacement systems. The phases P, S, and R for Rayleigh are identified on these vertical records. The arrows delimit the windows used to compute the spectra. Noise spectrum shown by dashed line.

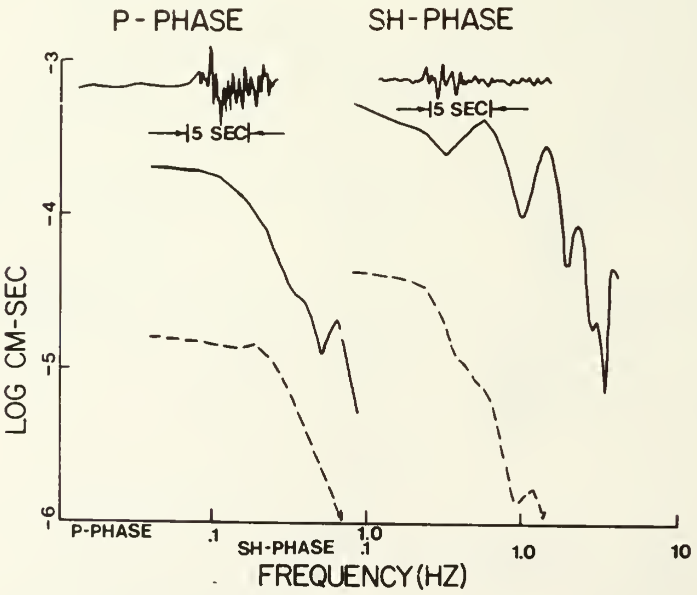

Figure 4. The 02 August 2023 GCT event as recorded at Berkeley vertical (P) and N45W (SH) instruments. Noise spectrum given by dashed line.

STRONG-MOTION SEISMOGRAPH RESULTS FROM THE OROVILLE EARTHQUAKE OF 1 AUGUST 1975

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INTRODUCTION

In 1963 the Seismological Field Survey of the Coast and Geodetic Survey (now the Seismic Engineering Branch - USGS) instituted a cooperative program with the California Department of Water Resources (CDWR) to locate strong-motion seismographs on and near critical facilities being developed as part of the California State Water Project. In the following year, an accelograph and seismoscope were installed at a seismograph station 2 km northeast of the intended site of Oroville Dam and four seismoscopes were located on sites representative of various soil conditions in the town of Oroville. Following completion of the dam, accelerographs were installed in the core block and on the crest. In 1973, during implementation of the State of California strong-motion instrumentation program, the Division of Mines and Geology (DMG) established accelerograph stations at four outlying locations within 35 km of Oroville.

As a result of these earlier actions, important records of the Oroville earthquake (rated magnitude 5.7 by Berkeley and magnitude 5.9 by the USGS) were obtained from five accelerographs and five seismoscopes located between 8 and 33 km of the earthquake epicenter. An additional 12 acceleration records, none showing significant motion, were recorded at stations between 80 and 148 km from the epicenter.

Results from these accelerograph and seismoscope records presented in this report include calculated velocities, displacements, and Fourier spectra for the data recorded at Oroville dam crest and the nearby seismograph station. Tripartite response spectra are shown for the seismograph station record.

ACCELEROGRAPH RECORDS

Data Recovered

A summary of the acceleration data recorded during the Oroville earthquake, listed in Table 1, includes the maximum accelerations, epicentral distances based on the Berkeley epicenter of 39.44°N and 121.53°W, and soil conditions at the 5 sites where relatively significant motions were recorded. The locations of the nearer stations are indicated on Figure 1.

TABLE 1. SUMMARY OF ACCELEROGRAPH DATA FROM THE OROVILLE EARTHQUAKE

Station	Epicentral Distance (km)	Soil	Component	Maximum Acceleration (g)
Black Butte Dam	80			Minor record
Chico	33	Alluvium	S33W	.08
			Down	.03
			S57E	.06
Garnier Ranch	135			Minor record
Martis Creek Dam	122			5 minor records
Marysville	32	Alluvium	S85W	.07
			Down	.04
			S05E	.06
Oroville Dam* Crest	11	Earthfill dam	N46E	.12
			Down	.13
			N44W	.09
Oroville Dam Seismograph Station	12	Meta-volcanic rock	N53W	.10
			Up	.12
			N37E	.11
Paradise	32	Volcanic rock	S07E	.03
			Down	.03
			N83E	.04
Peripheral Canal	125			Minor record
Rancho Seco	127			Minor record
Reno, Nevada	148			Minor record
Stampede Dam	123			2 minor records
Sutter Buttes	35	Andesitic rock		Not triggered

* First few seconds of record lost.

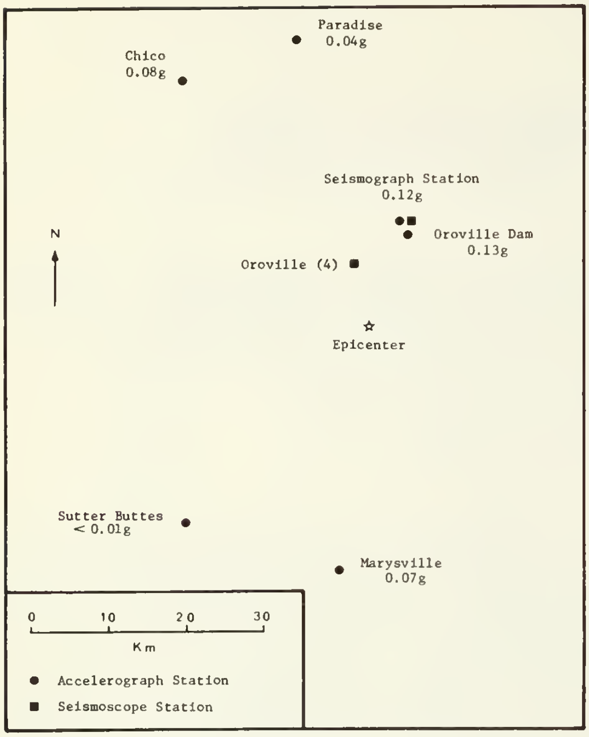


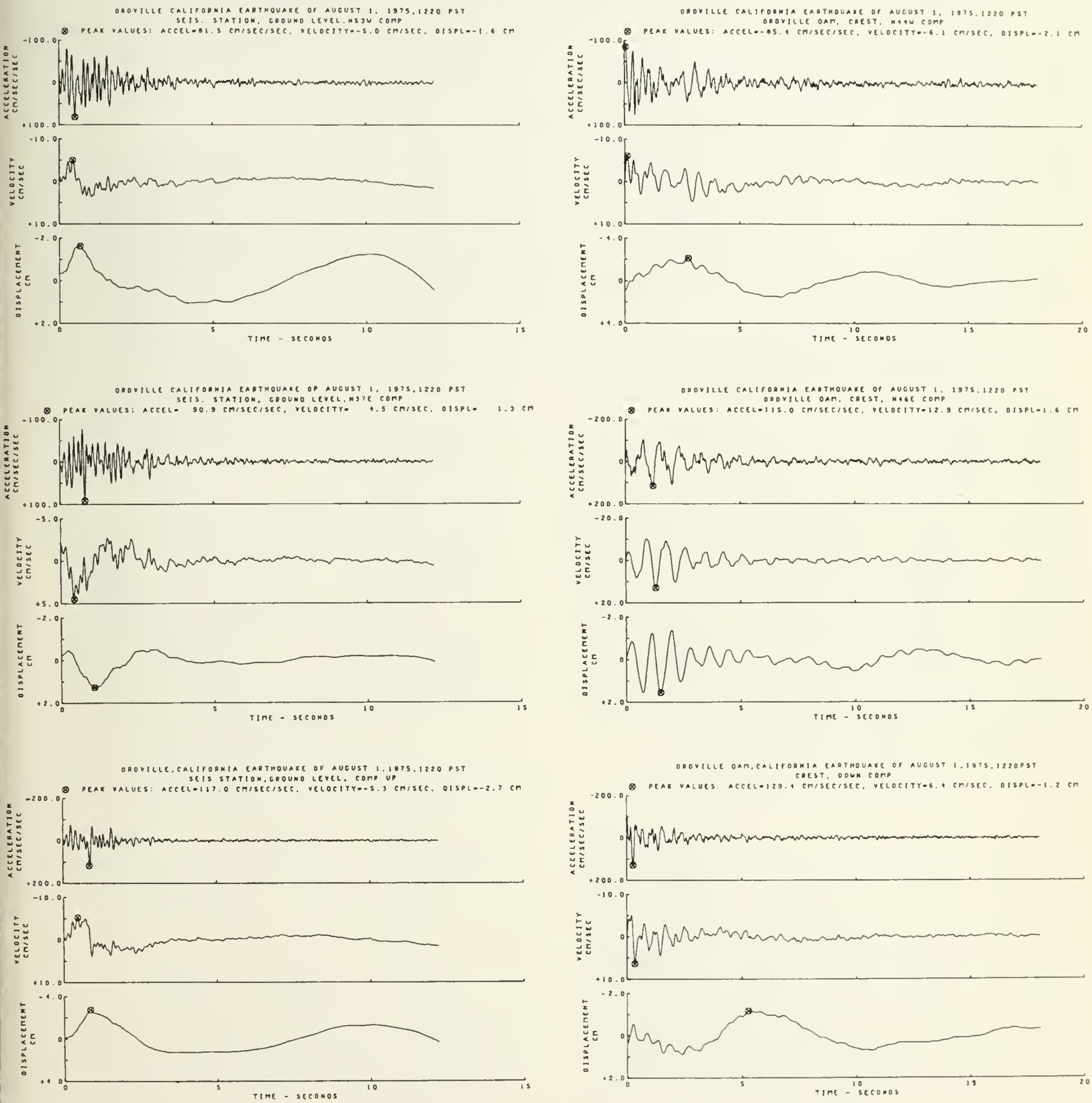
Figure 1. Location of strong-motion seismographs near the Oroville earthquake showing peak recorded accelerations. No record was obtained at Sutter Buttes; the maximum acceleration at this site is assumed to be less than the instrument's triggering threshold of 0.01g.

The records from the seismograph vault and the dam crest (Figure 2) show approximately 2 to 3 seconds of significant motion with maximum accelerations of 0.12 and 0.13 g. Other than these few peaks, the nominal acceleration values at and near Oroville Dam were somewhat less then 0.10 g. Note the obvious difference between the character of the N 46° E trace recorded transverse to the axis of the dam crest and the N 44° W trace recorded parallel to the crest axis. The longer period (approximately 0.84 second), somewhat sinusoidal motion of the N 46° E component is presumably produced by the dam responding in one of its transverse modes. The crest record was shortened a few seconds owing to a delayed start and consequently the earliest part of the earthquake was not recorded. A third accelerograph located in the core block of the dam was inoperative at the time of the earthquake.

Three other records were obtained from DMG instruments located at epicentral distances between 28 and 34 km. At two alluvial sites, Chico to the north and Marysville to the south, peak accelerations of 0.08 and 0.07 g respectively were recorded, while at Paradise, a rock site to the north, the maximum acceleration was 0.04 g. The instrument at Sutter Buttes installed in a building erected on volcanic rock, though operational, was not triggered by the earthquake. Since the vertical trigger at this site is calibrated to start the instrument at 0.01 g, the vertical accelerations were assumed to be somewhat less than this value.

Several minor records were obtained from outlying stations as far away as Sacramento and Reno, Nevada. A foreshock was registered at Oroville Dam crest and a number of aftershocks were recorded at the Oroville stations and at Chico and Marysville.

The amplitude and duration of the Oroville earthquake records appear to be perhaps slightly less than what normally might be expected from a magnitude 5.7 - 5.9 earthquake. A comparison of these peak accelerations with the attenuation curves for peak accelerations in rock published by Schnabel and Seed (1973) shows that the values recorded during the Oroville earthquake fall on the lower side of their attenuation envelope for earthquakes in the magnitude 5.6 range (Figure 3). The envelope is defined by Schnabel and Seed as the ". . . upper and lower bounds within which maximum acceleration are likely to lie, together with average values" for a particular range of magnitudes. The Oroville records show a level of peak ground shaking closer to that observed in other earthquakes in the middle 5 magnitude range not included in the Schnabel and Seed study. For instance, data reported from 6 ground stations that recorded the magnitude 5.4 Lytle Creek earthquake (Maley, 1971) show a scatter band of peak accelerations between 13 and 53 km, consistent with that recorded during the Oroville earthquake. Peak accelerations measured during the magnitude 5.5 June 7,



OROVILLE CALIFORNIA EARTHQUAKE OF AUGUST 1, 1975,1220 PST
SEIS. STATION, GROUND LEVEL,N53W COMP
⊗ PEAK VALUES: ACCEL=81.5 CM/SEC/SEC, VELOCITY=-5.0 CM/SEC, DISPL=-1.6 CM

OROVILLE CALIFORNIA EARTHQUAKE OF AUGUST 1, 1975,1220 PST
OROVILLE DAM, CREST, N44W COMP
⊗ PEAK VALUES: ACCEL=-85.4 CM/SEC/SEC, VELOCITY=-6.1 CM/SEC, DISPL=-2.1 CM

OROVILLE CALIFORNIA EARTHQUAKE OF AUGUST 1, 1975,1220 PST
SEIS. STATION, GROUND LEVEL,N37E COMP
⊗ PEAK VALUES: ACCEL= 90.9 CM/SEC/SEC, VELOCITY= 4.5 CM/SEC, DISPL= 1.3 CM

OROVILLE CALIFORNIA EARTHQUAKE OF AUGUST 1, 1975,1220 PST
OROVILLE DAM, CREST, N46E COMP
⊗ PEAK VALUES: ACCEL=115.0 CM/SEC/SEC, VELOCITY=12.9 CM/SEC, DISPL=1.6 CM

OROVILLE,CALIFORNIA EARTHQUAKE OF AUGUST 1,1975,1220 PST
SEIS STATION,GROUND LEVEL, COMP UP
⊗ PEAK VALUES: ACCEL=117.0 CM/SEC/SEC, VELOCITY=-5.3 CM/SEC, DISPL=-2.7 CM

OROVILLE DAM,CALIFORNIA EARTHQUAKE OF AUGUST 1,1975,1220PST
CREST, DOWN COMP
⊗ PEAK VALUES: ACCEL=129.4 CM/SEC/SEC, VELOCITY=6.4 CM/SEC, DISPL=-1.2 CM

Figure 2. Corrected accelerograms and their corresponding calculated velocities and displacements for Oroville Dam crest and the seismograph station. Note that contrary to general practice, the positive values are down and the negative values up. Because the accelerograph registers the negative of true acceleration, the y-axis is labeled to retain the normal accelerogram pattern.

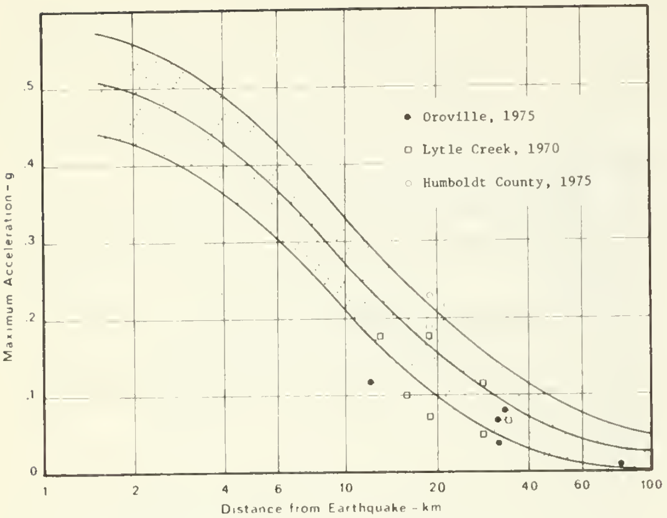


Figure 3. Maximum accelerations in rock for earthquakes of magnitude 5.5 to 5.8 (from Schnabel and Seed, 1973). The solid symbols represent data recorded during the Oroville earthquake out to 100 km.

1975 Humboldt County earthquake (Nason and others, 1975) also show a scatter band between 19 and 46 km that is comparable to Schnabel and Seeds magnitude 5.6 attenuation envelope but with somewhat larger amplitudes than those measured during the Oroville earthquake. Although duration studies have not yet been completed, all indications to this time point to an earthquake that in a strong-motion sense is somewhat less than a typical magnitude 5.7 - 5.9 event and perhaps more in line with an event in the middle 5 magnitude range.

Record Processing

Accelerograms from the seismograph station and the Oroville Dam crest were digitized on a Calma 685 model data digitizer and the records were processed using standard methods first developed at Caltech (Hudson and others, 1969). The scaled data were then corrected by performing an instrument correction and by bandpass filtering between 0.07 and 25 Hz (Hudson and others, 1971). Removing the frequency components shorter than 0.07 Hz provides the base line correction. The resulting accelerations and computed velocities and displacements are shown in Figure 2. The corrected data contains 50 equally spaced points per second, which corresponds to the Nyquist frequency of 25 Hz. Any difference in maximum acceleration between the actual accelerogram as listed in Table 1 and Figure 2 is produced primarily by the interpolation from unequally spaced uncorrected data to equally spaced corrected data, and secondly, the filtering.

One other aspect of the plots in Figure 2 needs further explanation. It is apparent in some of the displacement plots, and marginally apparent even in one velocity plot, that some long-period noise is still present in the data, for example, the approximate 8-second displacement period in the crest record, N 44° W component. There are no frequency components with periods longer than the routine cutoff period of 14 seconds (and roll-off termination at 20 seconds) but it is evident here that this cutoff period is in fact too long. The cause for this lies in the very low amplitude of acceleration for much of the duration of the records and the consequent lowering of the signal-to-noise ratio, as this noise arises primarily from random digitization errors and is independent of the acceleration amplitude. With this in mind and the fact that the records have only a 12-second duration anyway, a cutoff period considerably lower than 14 seconds should be used to remove these components from the acceleration data. In routine processing, it is not yet practical to examine each accelerogram in sufficient detail to permit selection of a cutoff period optional for that particular record.

Fourier spectra, Figure 4, were obtained for the accelerograms of the seismograph station and at the crest of the dam. The Fourier amplitude spectra indicate the frequency content of both accelerograms, that for the seismograph station expressing the predominant ground frequency components, that for the dam its modal response. The record from the seismograph station shows predominant periods of about 0.2 second, whereas the crest horizontal components indicate

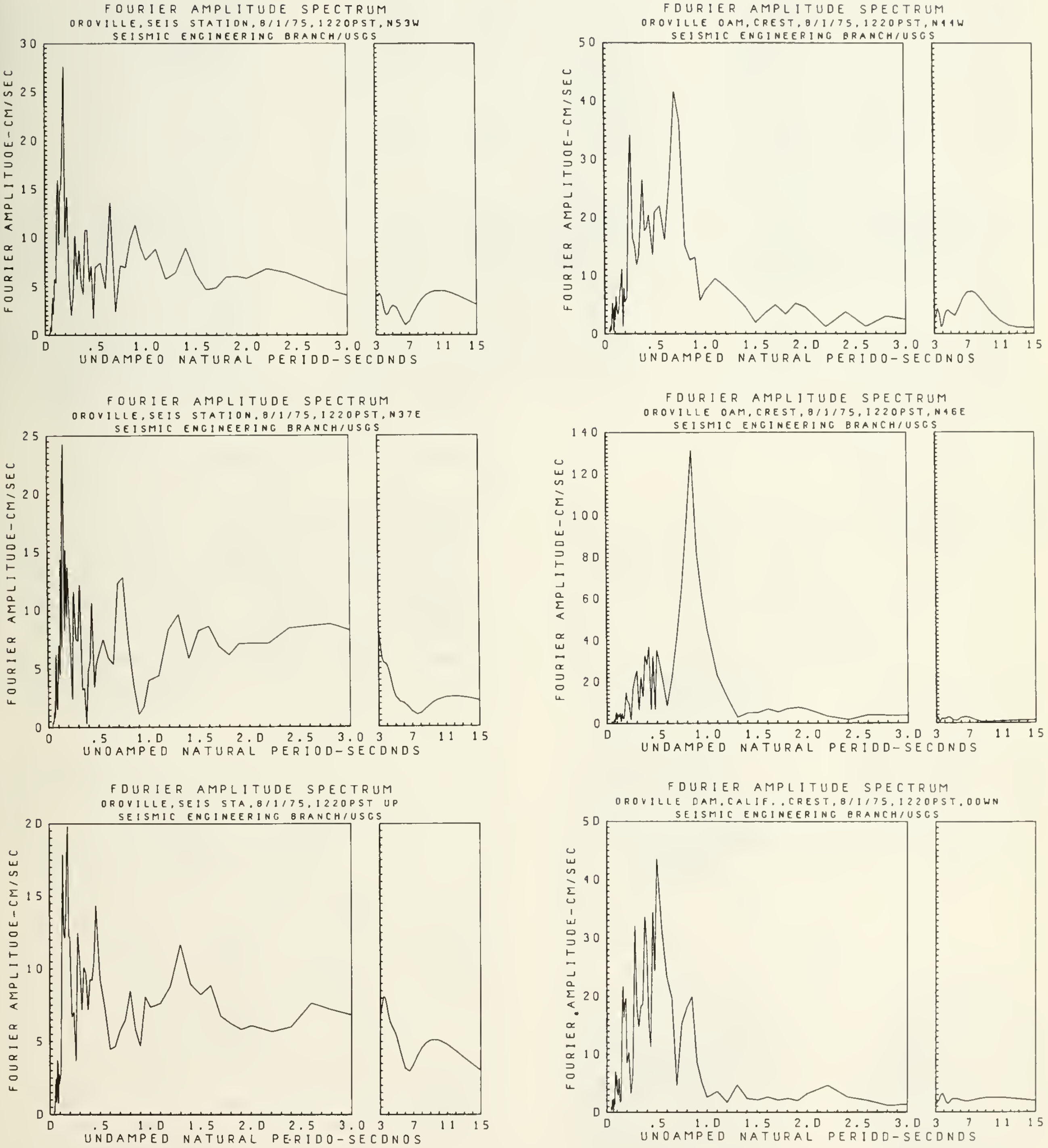


Figure 4. Fourier amplitude spectra from Oroville Dam crest and the seismograph station.

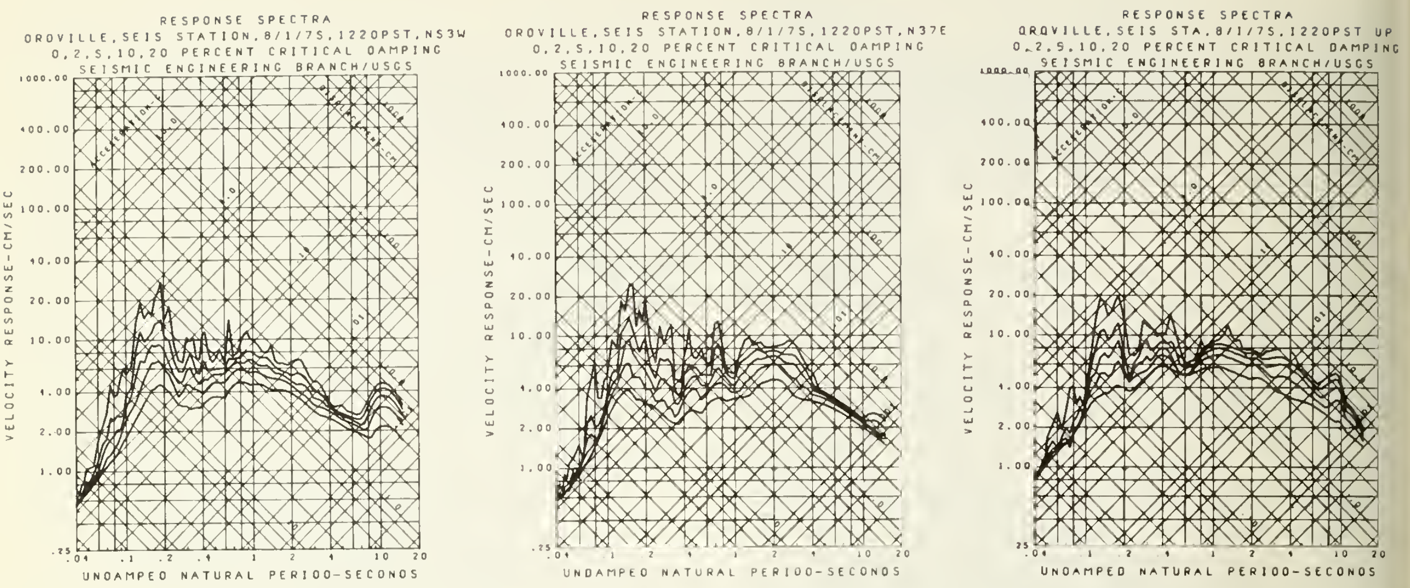


Figure 5. Pseudo-velocity response spectra calculated with 0, 2, 5, 10 and 20 percent critical damping for Oroville Dam crest and the seismograph station.

modal responses of about 0.84 second. The pseudo-velocity response spectra for the seismograph station are shown in Figure 5. The tripartite plots are for 0, 2, 5, 10, and 20 percent of critical damping; the frequencies chosen for the calculations are in the range 0.07 to 25 Hz.

SEISMOSCOPE RECORDS

Seismoscope records were obtained from four sites at Oroville (Figure 6) and from the seismograph station near Oroville Dam. All of the instruments were located in small one-story structures that existed at the time of installation in 1964. Records from four of the stations were collected on August 1 shortly after the main shock, whereas the Division of Highways record was not recovered until August 4. Consequently, the records are a composite of all earthquakes occurring up to the time of recovery but as these other earthquakes in the limited time interval were relatively small, each record represents principally the motion of the main shock.

Maximum relative displacement at the seismoscopes natural period of 0.75 second ranged from 0.9 cm at the seismograph station, 12.5 km epicentral distance, to 4.2 cm at the Division of Highways (DOH), 7.5 km epicentral distance. (See Table 2.) These Oroville data compare with data reported for the

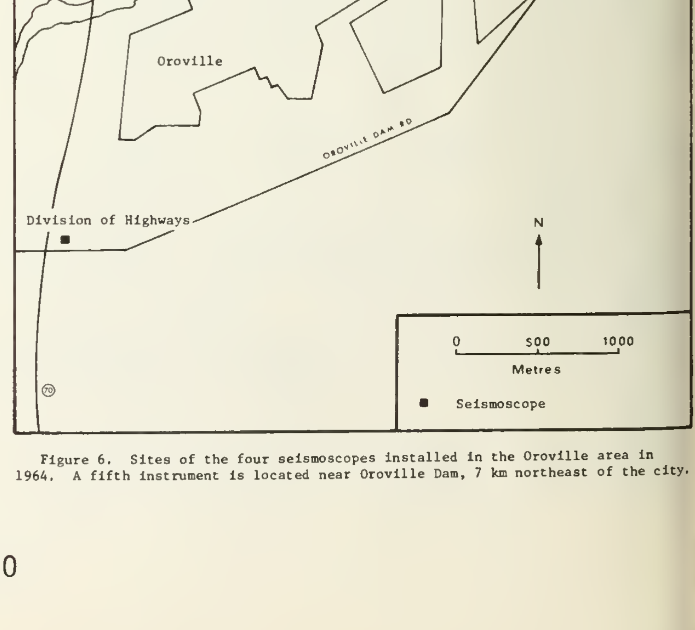


Figure 6. Sites of the four seismoscopes installed in the Oroville area in 1964. A fifth instrument is located near Oroville Dam, 7 km northeast of the city.

TABLE 2. SEISMOSCOPE RESULTS FROM THE OROVILLE EARTHQUAKE

Station	Direction to Epicenter (Degrees)	Epicentral Distance (km)	Soil	S_d (cm)	S_d Direction (Degrees)
Division of Highways	150	7.5	Alluvium	4.2	238*
Division of Forestry	161	10.6	Compacted clay, silt and sand	2.7	047
Fire Station	163	8.2	Compacted clay, silt and sand	1.6	275
Hill Residence	181	9.7	Volcanic and sedimentary rock	1.0	270
Seismograph Station	190	12.5	Meta-volcanic rock	0.9	106

* Corrected 50° counterclockwise.

magnitude 5.6 Parkfield earthquake of 1966, where relative displacement values ranged from 3.0 to 0.9 cm between 6.5 and 15.0 km of the fault rupture (Cloud, 1966). For the magnitude 5.4 and 5.6 earthquakes that occurred at Fairbanks within 9 to 19 km of the seismoscope stations, reported relative displacement values ranged from 5.0 to 1.7 cm (Cloud and Knudson, 1967). These comparative data sets again confirm that the Oroville earthquake produced local ground shaking effects equivalent to an earthquake of middle 5 magnitude.

Enlargements of the initial set of seismoscope records are shown in Figure 7. Note the larger amplitudes displayed by those instruments located toward the west as shown at the Division of Forestry and DOH stations. At DOH there was an offset in the zero position of the stylus either during the later part of the main earthquake or some time shortly thereafter, indicating apparent tilting of the order of 5 degrees down to the southeast. The instrument was in good condition and the stylus arm knife edges were still properly seated in the pivots. The reason for the shifted zero position is not yet known. Two later records removed from this site, before the instrument was releveled and the pendulum adjusted on August 8, show that the stylus zero position was shifted toward the hasp. This observation indicated the initial record had a 50° counterclockwise error in apparent orientation and therefore an appropriate correction has been incorporated into Figure 7 and Table 2. The DOH record also exhibited a prominent pulsing or excitement of the natural frequency of the pendulum suspension which, in effect, places a time scale on the record, permitting recovery of the acceleration time history in later analysis. Some of the other records have this characteristic, particularly the Division of Forestry Station, and appropriate analyses will be performed.

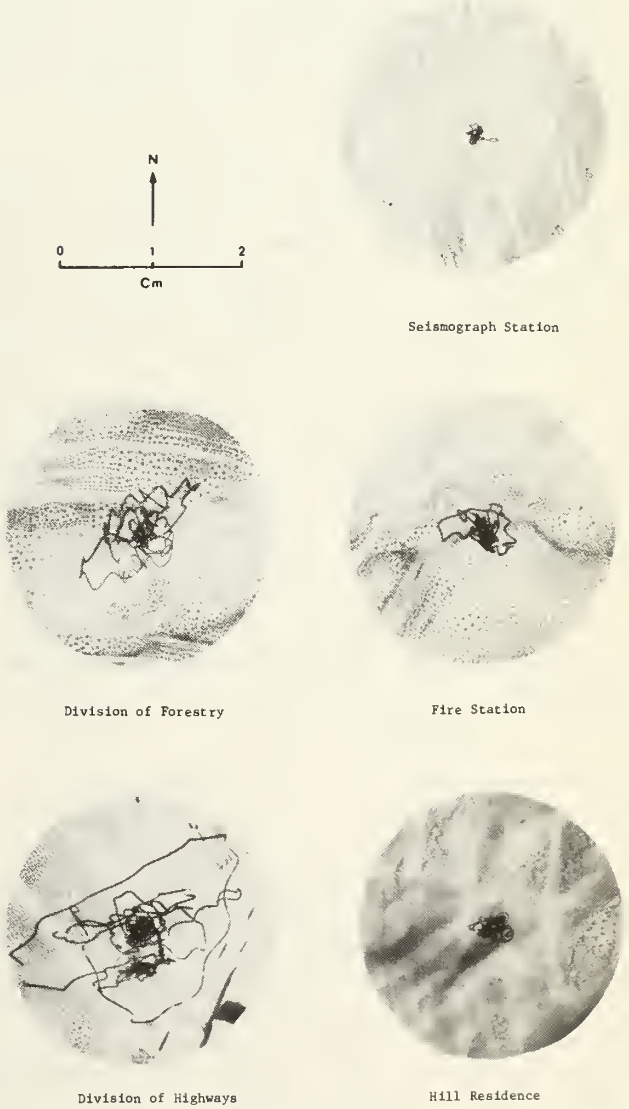


Figure 7. Copies of seismoscope records enlarged 2-1/2 times. Note the relatively large amplitudes exhibited by those records obtained furthest to the west.

SUMMARY

Records from 17 accelerographs and 5 seismoscopes were obtained from the magnitude 5.7 - 5.9 Oroville earthquake that occurred on 1 August 1975. The nearest acceleration data were recorded on the Oroville Dam crest and at the adjacent seismograph station located 11 and 12 km, respectively, from the earthquake epicenter. Significant motion lasted only 2 to 3 seconds at these sites and although nominal accelerations were somewhat less than 0.10 g, acceleration peaks were 0.13 g at the dam crest and 0.12 g at the seismograph station. Other records obtained between 28 and 34 km of the earthquake epicenter showed maximum acceleration of 0.07 to 0.08 g on alluvium and 0.04 g and less on rock.

The records from the dam crest and the seismograph station were digitized and the resulting time histories of accelerations, velocities, and displacements have been calculated. Fourier spectra obtained for the same records show the existence of many frequency components with a dominant period centering on 0.2 second at seismograph station and 0.84 second at the dam crest, the period of the dam reflecting a transverse modal response of the dam.

Seismoscope records obtained between 7.5 and 12.5 km of the earthquake epicenter show relative displacement responses ranging from 4.2 to 0.9 cm.

ACKNOWLEDGMENTS

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MICRO-AFTERSHOCK STUDY OF THE OROVILLE, CALIFORNIA, EARTHQUAKE SEQUENCE OF AUGUST 1975*

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INTRODUCTION

Within two hours following the occurrence of the magnitude 5.7 earthquake near Oroville, California, at 2020 GMT on August 1, 1975, Woodward-Clyde Consultants began to mobilize a team of geologists and seismologists to go to the epicentral area. Early reports of this earthquake suggested that this earthquake could be of substantial importance in evaluating the tectonics of the northern Sierra foothills and reservoir-induced seismicity. With this objective we installed an array of four microearthquake recorders beginning less than 24 hours after the main shock. These recorders continuously monitored the aftershock sequence for 30 days. The early results of the seismic monitoring were used to assist in locating areas for geologic field studies (Cluff and others, 1975). In this paper, we report on our preliminary seismological studies of the main features of the aftershock sequence in the context of a brief review of historical seismicity.

HISTORICAL SEISMICITY

The occurrence of occasional moderate earthquakes in northern California for the past 125 years is reported in catalogs prepared by Townley and Allen (1939) and Bolt and Miller (1975). Table I lists the larger of these earthquakes and some of their principal features. Considering this reported historical pattern of seismic activity in the northern Sierran foothills region, the Oroville earthquake does not appear to present any strikingly anomalous features. In particular, the earthquake sequence in 1909 near Downieville, California, seems quite similar to the Oroville sequence. The main shock occurred on June 22, 1909, and was of possibly slightly lower maximum intensity than the main Oroville event. It was preceded by possible foreshocks on April 9, and was followed by a substantial aftershock sequence that lasted at least three weeks. The aftershock series was most severe immediately after the main shock and included several events whose intensity approached that of the main shock. In contrast, the 1940 earthquake northeast of Chico was of exactly the same reported magnitude as the Oroville shock, but had no reported fore- or aftershocks (Bolt and Miller, 1975). The other earthquakes listed in Table I were generally smaller and were followed by unremarkable or unreported aftershock sequences.

INSTRUMENTATION AND DATA ANALYSIS

Beginning on the morning of August 2, 1975, following the main shock, four smoked-paper recorders (Sprengnether MEQ-800) with single vertical seismometers (Mark Products L-4C) were installed in the epicentral area shown in Figure 1. Early reports placed the epicenter of the main shock somewhat west of Palermo. The first station (WC2) was installed in this area. A comparison of S-P times at this first station, at the California Department of Water Resources station (ORV), and from a brief monitoring period near Wyandotte indicated that the aftershocks were occurring to the east of Palermo. This information guided the installation of the other three stations at the locations shown in Figure 1. This station distribution

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*Modified from paper presented at First International Symposium on Induced Seismicity, September, 1975, Banff, Alberta, Canada.

Table I - Significant Earthquakes in the Northern Sierra Foothills

Date	Maximum Intensity and/or Magnitude	Location	Reported Aftershocks	Data Source
24 Jan 1855	VI-VII	Downieville, Sierra Co.	None	Townley and Allen (1939)
1 Dec 1867	VII	Nevada City	None	Townley and Allen (1939)
27 Dec 1869	VIII	Oroville (?)	None	Townley and Allen (1939)
24 Jan 1875	VI	Butte, Plumas, Sierra Cos.	Few	Townley and Allen (1939) Mountain Messenger (1875) Nevada Transcript (1875) Sacramento Union (1875)
28 April 1888	VIII	Nevada City	None	Townley and Allen (1939)
24 July 1903	VII	Willows	Several	Townley and Allen (1939) Sacramento Union Record (1903)
22 June 1909	VIII	Downieville	Many	Townley and Allen (1939)
8 Feb 1940	VI-VII 5.7	20 mi NE of Chico	None	Bolt and Miller (1975)
18 Nov 1942	VI	NE of Chico	None	Bolt and Miller (1975)
20 April 1945	VI	Paradise	None	Bolt and Miller (1975)
29 April 1968	VI 4.7	SW of Chico	None	Bolt and Miller (1975)

Note: Intensities for earthquakes prior to 1931 are Rossi-Forel.
Intensities for earthquakes during and after 1931 are Modified Mercalli.

provided adequate epicentral and focal depth control for events occurring in the aftershock zone.

In order to maximize earthquake identification and timing accuracy, drum speed was maintained at 2 mm/sec and records were changed twice daily for much of the month of operation. Drift of the station clocks was generally less than 0.01 sec/day. The number of events analyzed per day was restricted to no more than 10 to 20 earthquakes having magnitude greater than about 1.0 in order to provide a quickly available data sample of tractable size for the entire month of August. As recorded on 3-component stations in the area, S-waves were generally quite sharp on the vertical seismometers and were of similar character and arrival time to those recorded on the horizontal components (Ryall, personal communication, 1975). The records were read to 0.05 seconds using a magnifying reticule and readings were tabulated for both P and S arrivals. Through the cooperation of the University of California (Berkeley) Seismographic Station, readings from the ORV station were obtained and used in the

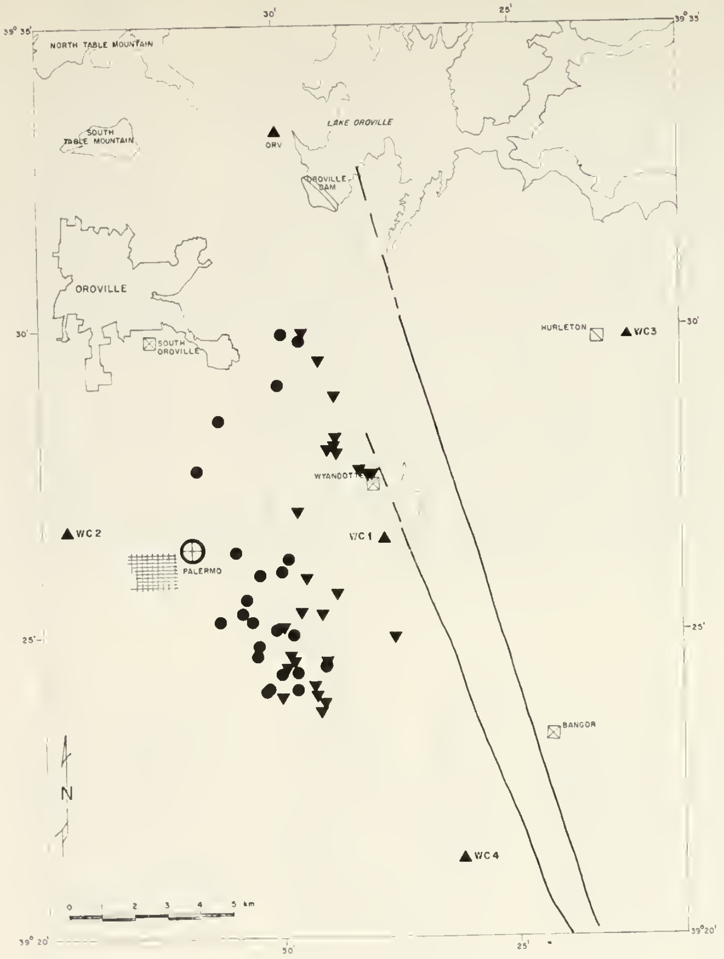

Figure 1. Epicenters located for the period August 2-4, 1975. Circles, focal depth $\underline{>}$ 5.5 km; inverted triangles, focal depth $\overline{<}$ 5.5 km. Large heavy circle with cross, main shock epicenter. Triangles, seismograph stations.

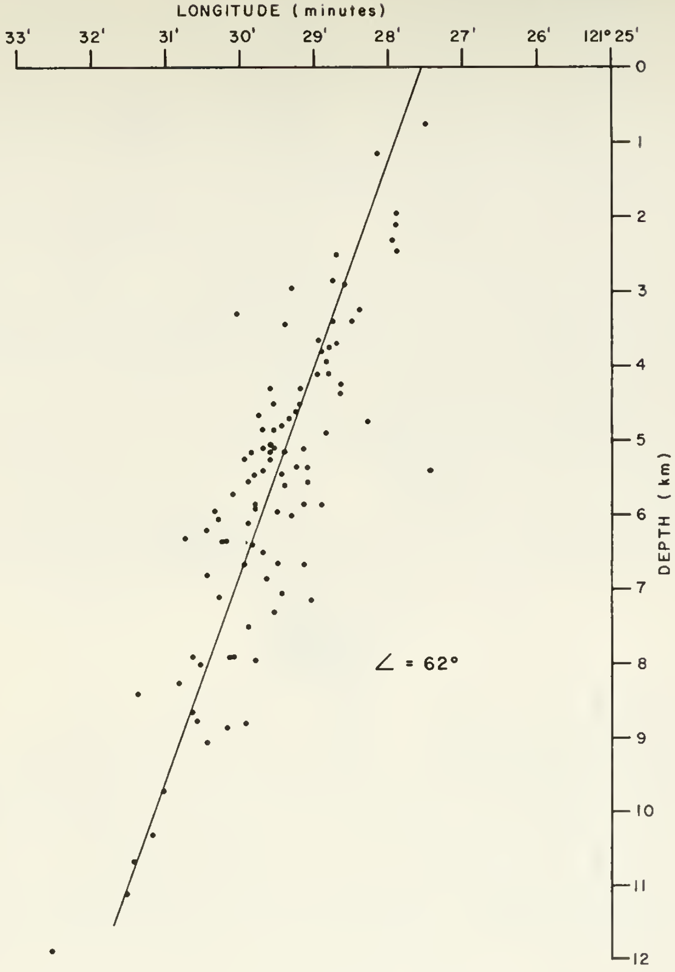

Figure 2. Hypocenters for first week projected on an E-W cross-section.

focal locations.

Epicenters for 243 earthquakes of the Oroville sequence are shown in Figures 1, 3, and 4. Focal coordinates were calculated using both P and S arrivals in the computer program HYPOELLIPSE (Lahr and Ward, 1975). A P-wave velocity of 5.9 km/sec for a half-space model was used based on the 6.0 km/sec velocity used by Ryall and others (1968) for the eastern side of the Sierras. Although this velocity may be somewhat high based upon recent work by the US Geological Survey (Bufe, personal communication, 1975), focal depths would be affected by less than 10 percent; for the purposes of this paper such errors are not significant. A much more accurate velocity model will be developed using a series of calibration explosions scheduled for mid-October, 1975. Relocations based upon this model will then be made available. Several earthquakes having good S-wave arrivals and that could be accurately located using only P-waves were used to calculate a P-to-S velocity ratio of 1.7. Thus all the earthquakes were located using both P and S arrivals from either four or five stations. Station corrections based on station elevations and an assumed 400 m thick layer of alluvium (V_p = 4.0 km/sec) at station WC2 were used in the calculations. Figures 1, 3, and 4 show only the 243 best locations, with standard errors in focal depth of less than 1 km, and in epicenter of less than 0.5 km.

The earthquakes shown in Figures 1, 3, and 4 are plotted to indicate the significant chronological changes in the pattern of hypocentral locations during the period from August 2 through September 1. Several features are apparent from the first two days of data (Figure 1):

1. The area of the aftershock zone two to three days after the main shock is roughly 100 km^2. The early aftershocks define a planar surface dipping steeply to the west almost 62 degrees (Figure 2) and having a strike trending approximately north-south. The projection of this planar zone intersects the surface of the earth along Cleveland Hill (shown in outline in Figure 1). A zone of ground cracking 1.6 km long was identified along Cleveland Hill in geologic field investigations following the main shock and may represent surface rupture of the aftershock zone (Cluff and others, 1975; Clark and others, 1975). The zone of cracking lies in the vicinity of the two pronounced topographic lineaments shown in Figures 1, 3, and 4.

2. The main-shock rupture appeared to originate along the western edge of the slip surface and then propogate updip to the east, as indicated by the location of the main shock with respect to the aftershocks. The epicenter of the main shock was determined by Morrison and others (1975) using aftershock locations determined in part from arrival time data from the instruments used in this study. Thus the main shock and its focal depth of 8 km are consistent with the aftershock locations as presented here.

3. There is an area of 25-50 km^2 along the western half of the aftershock zone that contains few aftershocks and may represent the central portion of the slip surface of the main shock. The distribution of aftershock activity defining the perimeter of this quiet zone suggests that the aftershocks may be produced by stress concentrations produced at the edges of the main shock rupture zone. There is an additional quiet zone in the epicentral region south of Wyandotte, which is the approximate site of two shallow, magnitude 5.1 aftershocks that occurred 24 hours after the main shock (Morrison and others, 1975). The zone of surface cracking mapped near Cleveland Hill serves to define the eastern edge of this quiet zone.

4. The aftershock activity at the southern end of the active area shown in Figure 1 is strongly concentrated and is distributed from almost 9 km to within 2 km of the surface. The after-

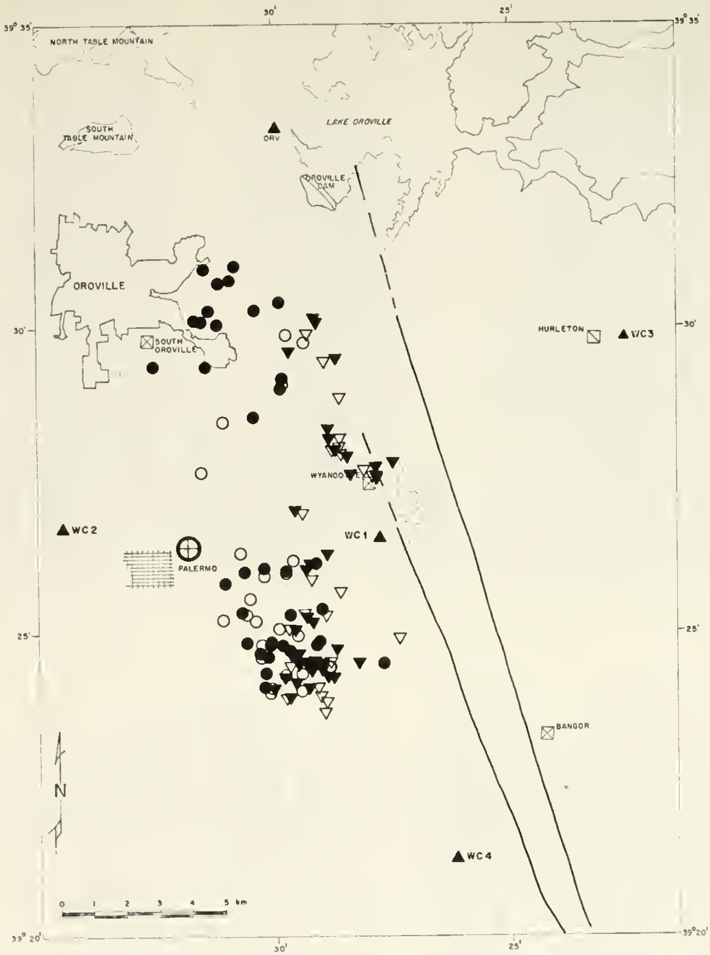

Figure 3. Epicenters located for the period August 5-14, 1975, closed symbols. Epicenters from Figure 1, open symbols. Circles, focal depth > 5.5 km; inverted triangles, depth < 5.5 km.

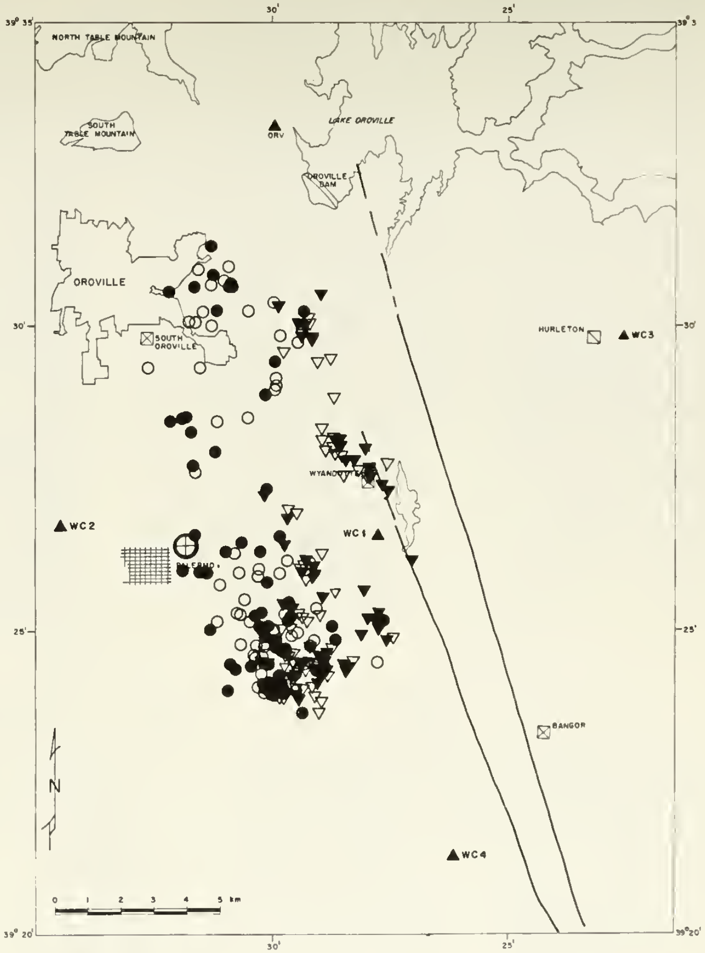

Figure 4. Epicenters located for the period August 15-September 1, 1975, closed symbols. Epicenters from Figures 1 and 3, open symbols. Circles, focal depth > 5.5 km; inverted triangles, depth < 5.5 km.

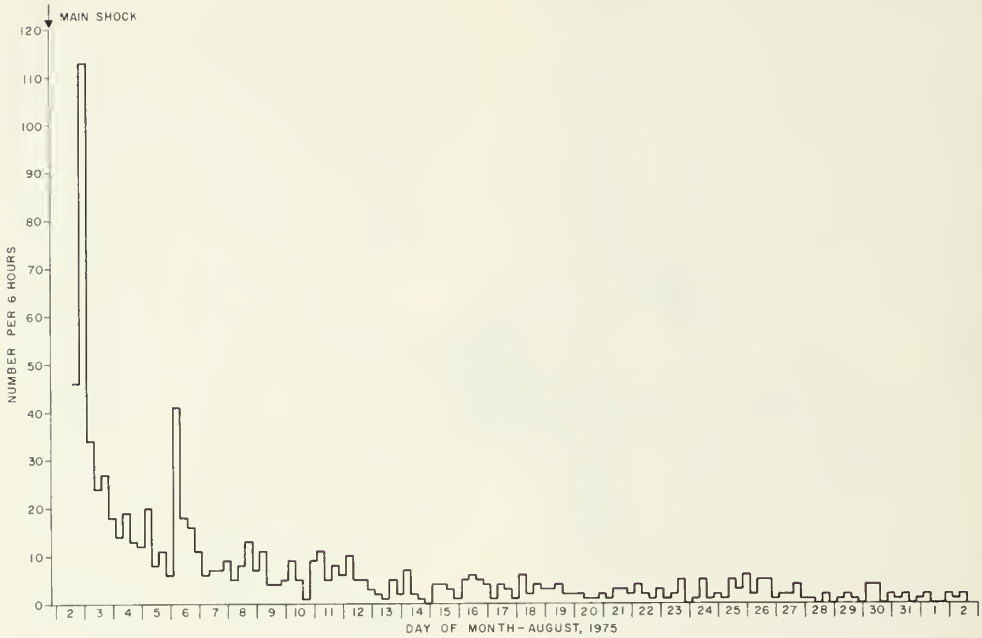

Figure 5. Aftershock frequency versus time. Daily number of shocks with magnitude ≥ 1 is proportional to $t^{-1.1}$.

shock activity to the northwest and northeast is not nearly so pronounced.

Beginning on August 5, several changes in the aftershock pattern emerged. As can be seen in Figure 3, there was a marked development of the aftershock zone toward the north at depths between 5 and 10 km. The area of the total zone increased by about 25 km^2. The quiet internal zones identified during the first few days of August were still well-defined, and the areal extent of the most active area to the south remained unchanged.

During the last half of the month of August (Figure 4), there was further modest growth of the aftershock zone to the north. The closest epicenters were located about 3 km from the Oroville Dam. The activity along the western edge of the rupture zone at a depth of 9-10 km increased, and there was some spotty filling-in of the central main-shock rupture zone.

The chronological sequence of microearthquake activity for events of magnitude greater than approximately 1.0 is shown in Figure 5. With the exception of two prominent secondary aftershock sequences, the frequency of occurrence decreases smoothly with time proportional to $t^{-1.1}$, where t is in days. This decay parameter of -1.1 is similar to that of other earthquake sequences in California and worldwide (Ranalli, 1969).

SUMMARY

The historical seismicity of the northwestern Sierran foothills, as defined by earthquake size and location and number of aftershocks, suggests that the 1975 Oroville earthquake sequence is not anomalous.

The temporal and spatial changes in the extent of the aftershock zone are consistent with growth of the zone due to the action of stress concentrations developed by the occurrence of the main shock. No direct relationship between the aftershock sequence and the presence of Oroville Reservoir was noted. An understanding of the substantial northward extension of the aftershock zone with time should be included in any model proposed for a reservoir-induced mechanism for the main shock.

The aftershock zone defines a planar surface dipping to the west and lies in close proximity to both a zone of surface cracking and trend of prominent topographic lineaments. Further detailed geologic and seismological analyses are needed to evaluate fully the relationship between the Oroville earthquake and the local and regional tectonic environment.

ACKNOWLEDGEMENTS

We wish to thank the Duffy, Lorain, Soden, and Trosin families in the Oroville area for their assistance in the data collection, Richard Thompson for his operation of the instruments, and Eric Von Dollen for the timely data processing. Helpful communications are also acknowledged from Alan S. Ryall, Thomas V. McEvilly, Charles G. Bufe, and the geology staff of Woodward-Clyde Consultants. The field program was supported in part by Pacific Gas and Electric Company as part of an ongoing nuclear power plant siting program. We also wish to thank Lloyd S. Cluff and Bruce C. Auld for their manuscript review and comments.

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AFTERSHOCKS OF THE OROVILLE EARTHQUAKE OF AUGUST 1 1975

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ABSTRACT

The epicentral area of aftershocks of the Oroville, California earthquake of August 1, 1975, extends from Oroville Dam 15 km to the south and from Palermo 7 km to the east. Aftershock hypocenters and focal mechanisms from P-wave first motions indicate normal faulting with the Great Valley side downdropped relative to the Sierra Nevada block along a surface striking north-south and dipping 60° to the west. Progressive growth of the aftershock zone and the position of foreshocks and main shock suggest that rupture began at depth near the western margin of the aftershock zone and propagated upward to the east along the fault plane. Later aftershocks indicate further extension of the rupture surface to the north and south, with several small shocks occurring near Oroville Dam in early October. The ratio of smaller to larger events was unusually low ($b = 0.6$) in relation to that reported for other earthquake sequences near reservoirs.

INTRODUCTION

The Oroville earthquake of August 1, 1975 was felt over an area of 120,000 km^2 with maximum intensity VII in the epicentral region and body wave magnitude of 5.9 (USGS National Earthquake Information Service). Local magnitude determinations range from 5.7 (BRK) to 6.1 (PAS). On August 2 installation of a network of short-period, vertical-component, telemetered seismographs was begun in the Oroville region by the U. S. Geological Survey (USGS). Work was completed on August 11 with a total of 16 stations installed (Fig. 1). Three horizontal-component seismographs were installed on September 6 at three of the original sites. Recording of aftershock data from the first five stations began on August 5. The data were first recorded at a site near Oroville Dam on an analog magnetic tape recorder. On August 15 data began being telemetered to Menlo Park and recorded on magnetic tape and 16mm develocorder films, and monitored in real-time by an on-line computer. Readings from these stations have been supplemented by readings from three local stations operated by the California Department of Water Resources (CDWR) and telemetered to Menlo Park through a data exchange program. Arrival times have been read from high resolution playbacks with an accuracy of ± 0.02 seconds relative to the Universal Time Code, WWVB. Locations for the period August 5-11 were determined using the HYPOELLIPSE Location Program (Lahr and Ward, 1975). Locations of foreshocks, the main shock, and earlier ($M \geq 3$) aftershocks were obtained from R.Uhrhammer, B. Stump, and P. Morrison (this volume), who used data from stations operated by CDWR, the University of California (BRK), and Woodward-Clyde Consultants.

AFTERSHOCK LOCATIONS

An aftershock zone has been defined (Fig. 2) for the period August 1-October 13 using locations of approximately 700 earthquakes. The zone is approximately 15 km long (NS) and 7 km wide (EW). By comparing foreshock, main shock, and aftershock locations, a pattern of faulting becomes apparent. Rupture began at depth near the western margin of the aftershock zone and propagated upward initially to the east, then to the north and south and finally extending some additional distance to the north. Since August 16, a real-time location system, using an on-line computer, has been used to monitor and locate earthquakes on a continuous basis. The epicentral locations determined using this system illustrate the slow, continued migration of aftershocks to the north and southwest (dotted lines in Fig. 2).

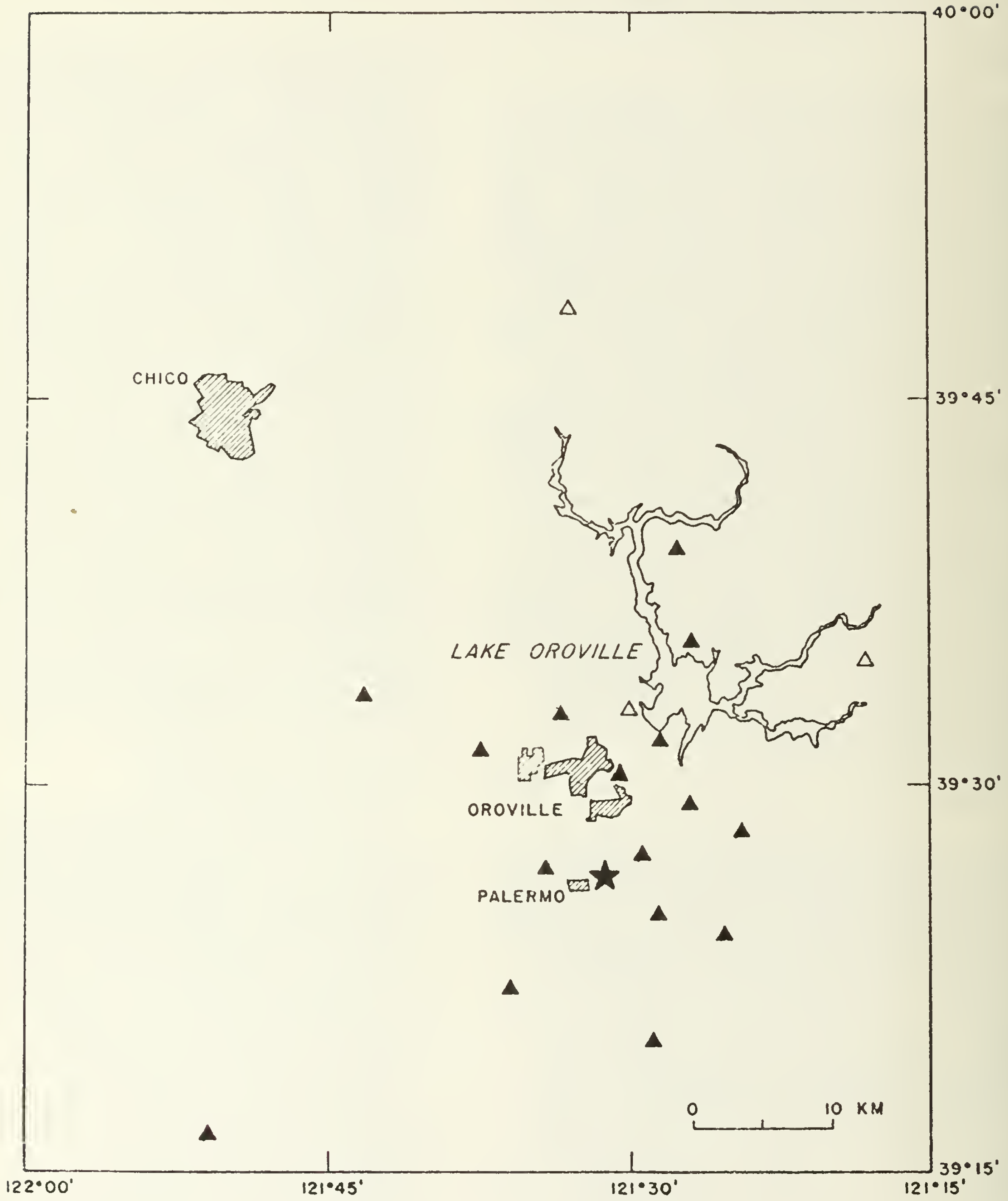

Figure 1. Map showing stations used to locate Oroville earthquakes. Solid triangles are USGS stations, open triangles are CDWR stations. The star indicates the location of the main shock. (BRK)

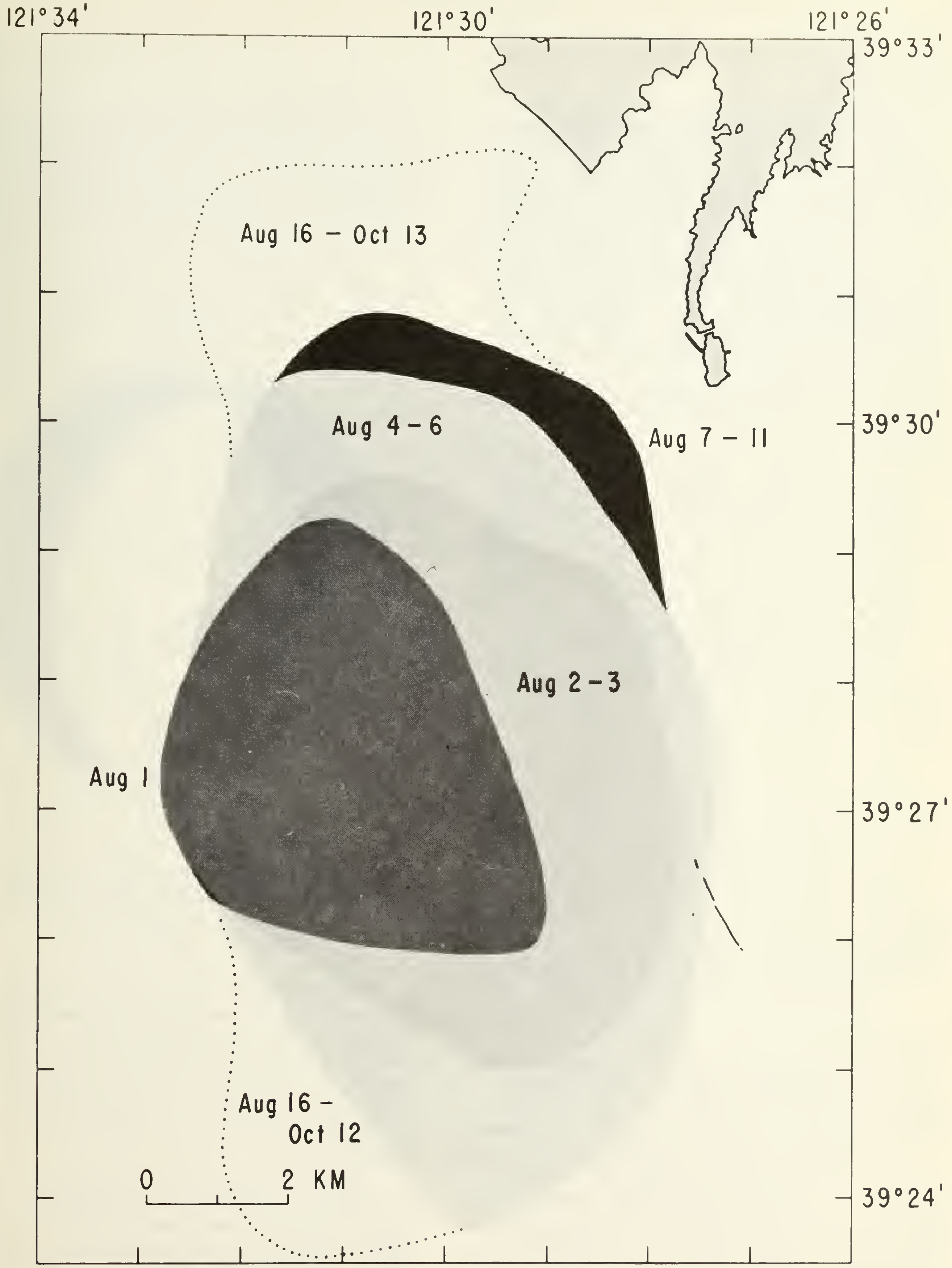

Figure 2. Progressive growth of the aftershock region.

FOCAL MECHANISMS AND FAULT PLANE ORIENTATION

Hypocenters for August 5-11 were projected onto vertical planes for different azimuths of view at 5 degree increments. Least scatter is seen looking due north, where a planar feature, which is assumed to be the fault surface, is defined by the upper edge of the hypocentral zone (Fig. 3). The apparent dip is to the west at approximately 60 degrees, steepening to nearly vertical at depth. The diffuse pattern of hypocenters below the apparent fault surface may indicate additional faulting in the lower block or the presence of local inhomogeneities in the velocity structure.

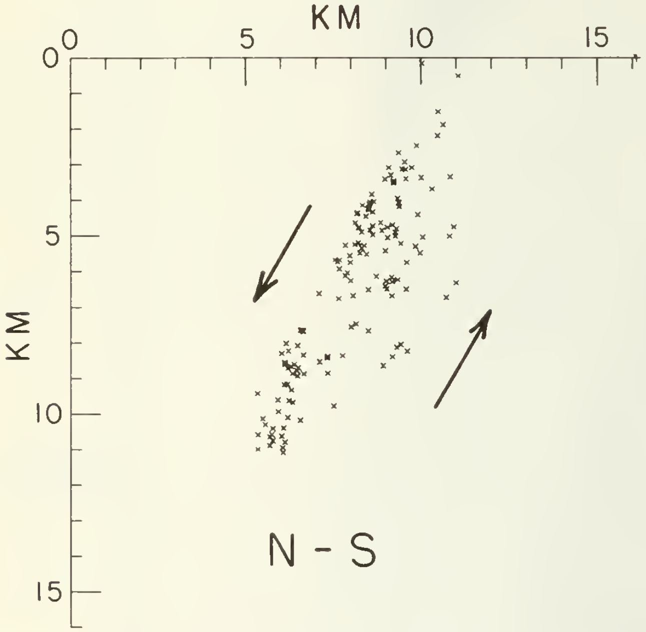

Figure 3. Vertical cross section through the hypocentral region of aftershocks (August 5-11). Aximuth of view is 0 degrees.

Fault plane solutions were constructed for the aftershock region. A solution typical of most of the areas of the aftershock region is shown in Figure 4. Zones of compression are illustrated by darkened areas. If the westward dipping plane is assumed to be the fault plane, normal faulting is indicated, with the Sacramento Valley block downdropped in relation to the Sierra Nevada block.

Fault plane solutions for subregions of the aftershock zone show substantial variations in strike and dip of the fault plane, but all solutions examined showed pure dip-slip with no significant component of strike-slip (Bufe et al, 1975).

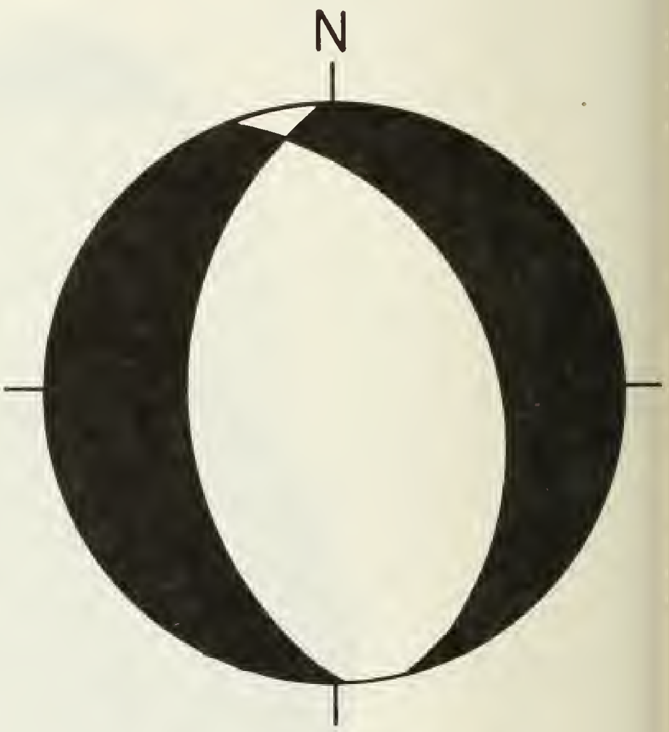

Figure 4. Fault plane solution (lower hemisphere) for the Oroville aftershock region. Darkened areas indicate zones of compression.

A newly formed, 1.6 km long surface rupture was mapped by Sharp and others (1975). This is located near the eastern boundary of the aftershock zone and is shown as the dashed line in Figure 2.

RELATIONSHIP OF THE EARTHQUAKE TO THE RESERVOIR

The relationship of earthquakes to reservoirs has been under study for some time. Reports from a number of locations have associated increased seismicity with reservoir filling. Results from fluid injection studies (Healy et al, 1968) suggest that fluid pressure rather than surface loading may play an important role in the triggering of earthquakes by reservoirs. These reports and the proximity of Lake Oroville to the recent earthquake activity raise the question of whether the earthquakes are reservoir-related.

The earthquake activity near Lake Oroville appears to be different from that observed near other reservoirs (Gupta et al, 1972) in several respects. Whereas increased seismicity usually begins shortly after the reservoir is first filled, no local earthquakes were observed when Lake Oroville was first filled to capacity in 1969 (Hoffman, 1973). The typical seasonal fluctuation of water level at Lake Oroville is about 20 m, although the level was lowered in excess of 40 m during the past winter and filled again to capacity with the spring run-off.

The recent earthquake activity in the Oroville area began on June 28, 1975, with a sequence of small ($M \leq 3.5$) shocks. A low level of activity continued until 1627 Greenwich Mean Time (GMT) on August 1 when a magnitude 4.7 (BRK) foreshock occurred. The main shock occurred 4 hours later at 2020 GMT, approximately 8 seconds after a large ($M = 4.5$) foreshock. The arrivals of the foreshock obscured arrivals for the main shock, thus rendering the location uncertain. Four months after the main shock earthquakes continue to occur at a rate of 2-3 per day ($M \geq 0$).

Although station coverage is relatively poor for many instances of reservoir-related earthquakes, epicenters usually appear to be confined to the vicinity of the dams and reservoirs. The main shock at Oroville occurred about 11 km from the dam. Aftershocks have migrated northward (Fig. 2) so that at least 1 aftershock ($M = 0$) has been located beneath the west face of the dam and several others are within 2-1/2 km of the dam. If the fault plane,which is assumed to be defined by the upper surface of the aftershock hypocentral zone , were projected northwards along strike, it would pass beneath the dam and outcrop under the reservoir.

Reservoir-related earthquakes discussed by Gupta et al (1972) are characterized by high b values ($b \geq 1.0$, relatively large numbers of small events) and a high magnitude ratio of the largest aftershock to the main shock (about 0.9). At Oroville, the ratio of BRK magnitude of largest aftershock to main shock is 0.9, but in contrast, b slopes are low (.43 for foreshocks, .62 for aftershocks), based on magnitudes derived from coda lengths.

PAST SEISMICITY

Information about seismicity since 1940 within 100 km of Lake Oroville, as compiled by the USGS National Earthquake Information Service, is shown in Table 1. None of these 40 events is closer than 40 km to the present activity. The occurrence of earthquakes within 100 km of Oroville does suggest relatively high regional tectonic stresses in the area, which are conducive to earthquake triggering, both by reservoirs and natural causes.

FUTURE SEISMICITY

In light of the data presented, important questions are raised concerning the possibility of future earthquakes at Oroville. Two earthquake sequences were chosen for comparison of time history to the Oroville sequence, and are illustrated in Figure 5. The Fallon, Nevada sequence (Slemmons et al, 1965) is an example of normal faulting and the Koyna, India sequence (Gupta et al, 1972) shows an example of reservoir related earthquakes. The Oroville sequence, to date, is shown in the center. If the earthquakes at Oroville are reservoir-related, experience elsewhere suggests that the increased level of seismicity could persist for years or decades, with the possibility of additional large events.

The main shocks at Oroville and Koyna have well-developed foreshock sequences, a pattern noted by Gupta et al (1972) as

Table I - EARTHQUAKES WITHIN 100-KM RADIUS OF OROVILLE, CA (39.5 N., 121.5 W.)

SOURCE	YEAR	MO	DA	HR	MN	SEC	LAT	LONG	DEPTH (KM)	MAGNITUDES			
										BODY	SURF.	OTHER	LOCAL
G-R	1940	02	08	08	05	59.0	39.750 N	121.250 W	035			6.00PAS	
CGS	1942	09	29	08	28	12.0	39.400 N	122.400 W					
CGS	1949	08	21	11	45	20.0	40.283 N	121.167 W				3.90PAS	
CGS	1949	08	21	20	48	16.0	40.267 N	121.233 W				4.50PAS	
CGS	1950	06	22	12	44	46.0	39.700 N	120.400 W				3.60PAS	
CGS	1950	06	22	17	13	18.0	39.700 N	120.400 W				4.10PAS	
CGS	1956	03	18	10	17	41.0	40.000 N	121.600 W					
CGS	1956	03	18	10	22	03.0	40.000 N	121.600 W					
PAS	1959	06	14	01	26	34.0	39.500 N	120.500 W	016A				4.30MLPAS
CGS	1960	06	28	06	41	32.0	40.317 N	121.033 W				3.60PAS	
PAS	1960	11	18	11	03	15.0	39.300 N	120.500 W					4.20MLPAS
USE	1962	01	08	10	48	49.0	40.200 N	121.000 W					
CGS	1963	07	08	05	35	31.0	40.200 N	121.000 W	033	3.50MB			
CGS	1964	10	27	00	32	21.9	40.100 N	121.700 W	014	4.40MB			
CGS	1965	08	29	18	25	15.7	39.700 N	122.100 W	033				3.63MLBRK
CGS	1965	12	12	12	57	50.0	40.400 N	121.600 W	022				
CGS	1965	12	26	03	29	36.1	40.200 N	121.500 W	010				
CGS	1966	04	24	00	47	02.6	39.700 N	120.400 W	033				3.60MLBRK
CGS	1966	05	24	03	49	52.8	39.700 N	121.900 W	002	4.50MB			4.60MLBRK
CGS	1966	09	12	18	42	49.1	39.500 N	120.400 W	033	4.40MB			
CGS	1966	09	22	08	44	18.1	39.500 N	120.400 W	033				
CGS	1966	09	22	22	45	10.9	39.400 N	120.400 W	033	3.80MB			
CGS	1966	09	25	13	05	40.5	39.500 N	122.100 W	013	3.50MB			
CGS	1967	02	03	15	35	08.6	39.473 N	122.046 W	013	4.00MB			3.40MLBRK
CGS	1968	02	26	02	51	26.4	40.000 N	121.100 W	004				
CGS	1968	04	02	16	15	18.0	40.100 N	120.900 W	033	4.40MB			
CGS	1968	04	04	21	08	58.3	40.000 N	120.900 W	033				
CGS	1968	04	29	00	21	36.6	39.500 N	122.100 W	018	5.00MB			
CGS	1968	07	22	01	05	01.3	39.789 N	121.898 W	005	4.10MB			
CGS	1970	04	23	05	26	14.8	40.283 N	121.386 W	010				3.60MLBRK
CGS	1970	07	01	07	55	26.3	39.488 N	122.044 W	012	4.30MB			3.30MLBRK
CGS	1970	07	81	18	56	59.5	39.481 N	122.071 W	011	4.20MB			3.20MLBRK
CGS	1970	07	06	11	52	29.7	39.245 N	122.407 W	022				3.00MLBRK
CGS	1970	09	20	08	37	21.5	40.290 N	121.312 W	008	3.90MB			
NOS	1970	12	09	09	35	50.9	40.176 N	121.316 W	033N	4.00MB			3.50MLBRK
ERL	1971	08	06	22	29	47.2	39.456 N	122.152 W	000				3.80MLBRK
ERL	1972	07	16	14	42	11.2	39.991 N	121.286 W	033N	3.80MB			
ERL	1973	06	06	06	20	35.9	39.795 N	122.118 W	003				3.60MLBRK
GS	1974	05	27	09	19	19.7	39.852 N	120.918 W	002	4.60MB			3.90MLBRK
GS	1974	09	29	01	26	48.9	39.914 N	121.788 W	010G				3.80MLBRK

typical of reservoir-related earthquakes. However, foreshock sequences are not uncommon in association with "tectonic" earthquakes in central California (Kodama and Bufe, 1975).

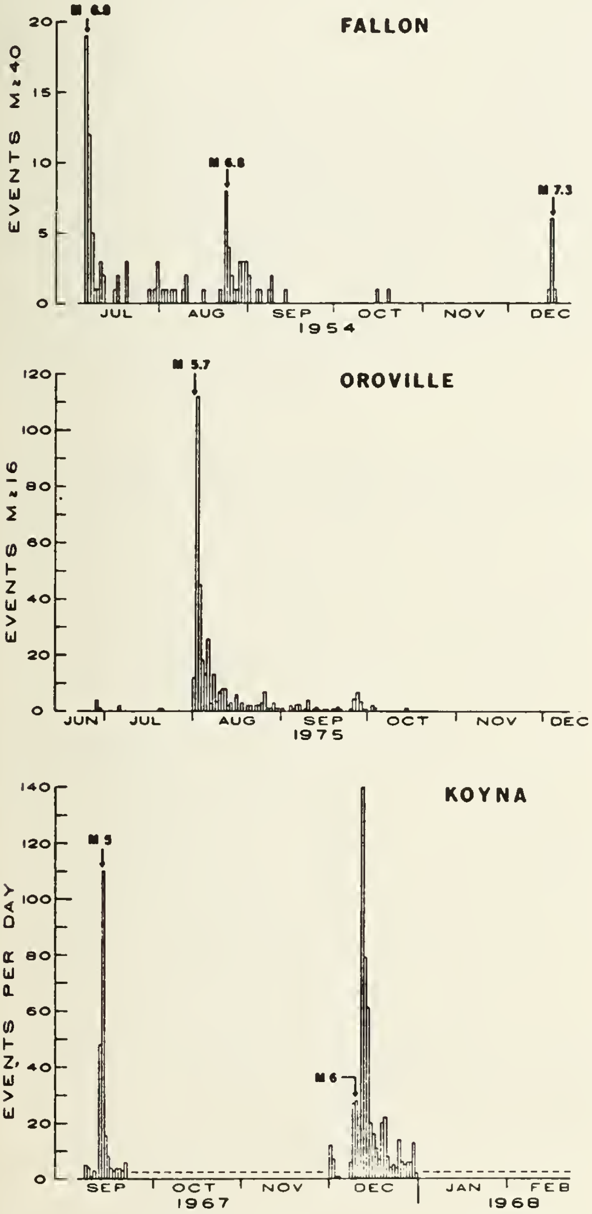

Figure 5. Comparison of earthquake sequences at Fallon, Nevada; Koyna, India; and Oroville, California.

CONCLUSIONS

The Oroville earthquake sequence is characterized by normal faulting, and a low b slope. The north-south strike of the hypocentral plane does not appear to relate to any clear evidence of surface faulting in the last several thousand years. While the location and orientation of the aftershock zone suggests the possibility that the earthquakes are reservoir-related, no conclusive evidence has been found that this is the case.

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FIELD-SEISMIC INVESTIGATION OF THE OROVILLE, CALIFORNIA, EARTHQUAKES OF AUGUST 1975

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INTRODUCTION

The Oroville earthquake of August 1, 1975 (M_L = 5.7) occurred in an area of relatively low historic seismicity, ten kilometers from Lake Oroville (height of dam 210 m, 4,364 x 10^6 m^3 capacity), seven years after initial filling of the lake but only a month after the most rapid filling since 1968 (L. Fredrickson, personal communication).

The main shock occurred eight seconds after a magnitude 4.5 foreshock, and according to T. V. McEvilly (personal communication), the two events were colocated (39° 26.3' N, 121° 31.7'W, depth 8 km). This location is on the eastern edge of the Great Valley of California, in a zone separating valley sediments to the west from Tertiary volcanics, Mesozoic intrusives and metavolcanics, and Paleozoic marine deposits of the Sierra Nevada foothills to the east. These are shown on Figure 1, together with mapped faults (California Resources Agency, 1973) and lineaments taken from a NASA Skylab photograph. In general, lineaments in the vicinity of Lake Oroville trend about N15°W, and those to the west trend N35°W - N40°W. One lineament on the Skylab photograph coincides with ground cracking observed just south of Wyandotte (39°25.9' N, 121° 28.1 W), and passes within two kilometers of the lake.

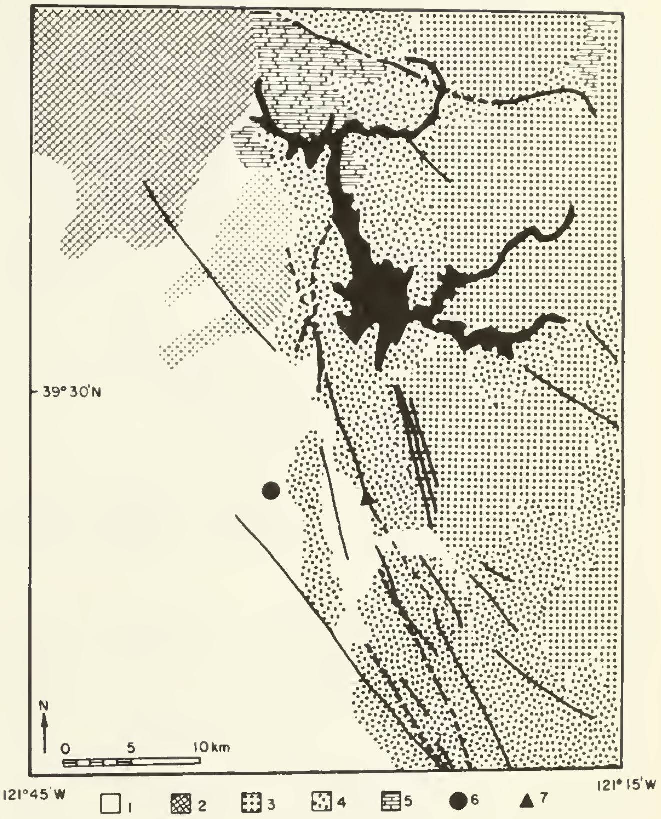

Figure 1. Map of the Oroville region, showing mapped faults (heavy lines) (California Resources Agency, 1973) and lineaments taken from a Skylab photograph (light lines). Black area is Lake Oroville. Patterns summarize geology (California Resources Agency, 1965): 1 -- valley sediments; 2 -- Pliocene/Eocene volcanics; 3 -- Mesozoic granites and basic intrusives; 4 -- Jurassic-Triassic metavolcanics; 5 -- Paleozoic marine deposits; 6 -- location of main shock; 7 -- location of surface cracking.

DATA AND ANALYSIS

The data for this investigation were obtained from field instruments plus a California Department of Water Resources station at the Oroville Dam. Station locations are shown on Figure 2. A single-component seismograph was used initially to sample S-P times within the epicentral area, and a small wire-linked array (HKN, HKC, HKS, HKW) was then installed about five kilometers south of Oroville Dam. This array began recording at 02h GCT on 3 August (i.e., 28 hours after the main shock), and continued until 27 August when the instruments were removed. A second, radio-telemetered array (SHR, RSK, KAB, COX) was installed on 6 August and removed on 27 August; one station of this array (SHR) did not begin

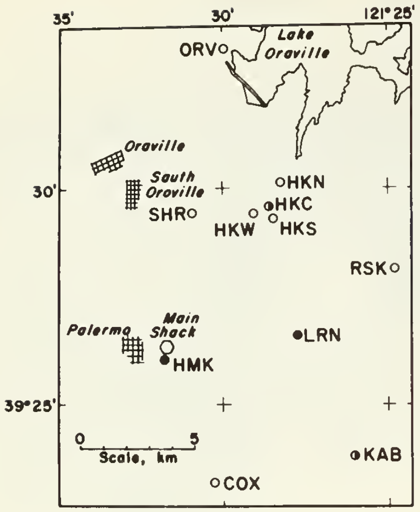

Figure 2. Station locations. Open circles -- high gain stations; closed circles -- strong-motion stations.

operation until 20 August. Seismic signals from both arrays were recorded on FM magnetic tape, together with a WWVB time signal. Events selected for detailed analysis were played out onto photographic strip-chart recordings; data quality was excellent, and arrivals could be timed to an accuracy of ± 0.02 second. The signal from station ORV was telemetered to Reno throughout the earthquake sequence, and it was recorded on tape as well as a Helicorder. Tape playbacks of the ORV signal were used in the analysis of selected events, and the Helicorder records were used to count events and measure event durations. Events subjected to detailed analysis were selected arbitrarily, in part for convenience in playing back tapes, and included 86 events on 7-8 August and 48 events on 17-19 August. Focal determinations were calculated using the USGS computer program HYPO71, assuming a 28-km thick crust with P-velocity of 6.00 km/sec.

In addition to the high-gain stations, four strong-motion instruments (Kinematics SMA-2 tape-recording accelerographs) were installed at stations KAB, HKC, LRN and HMK on 8 August, and these were removed on 27 August. Analysis of the strong-motion records is reported by Peppin (1975).

RESULTS

Of the 134 events selected for detailed analysis, 104 gave high-quality focal determinations, and the distribution of these events is shown on Figure 3 (closed circles -- 52 events before 08h, 8 August; open circles -- 52 events after 08h on 8 August). The focal coordinates were fit by least-squares to a plane, which had strike N07.2°W and dip 59.2°W. As shown by the dotted line on Figure 3a, the surface trace of this plane passed through the Oroville Dam and within 200 m of the cracking observed near Wyandotte; Figure 3b shows that the focus of the main shock was also very close to the plane. The solid circles on Figure 3c indicate that activity at the end of the first week of the sequence was concentrated at the ends of the focal zone, and Figures 3b and 3c give dimensions of the rupture zone of about 11 km by 17 km. Later activity appears mainly to have filled in the region around the main shock. Average focal depth for the first 52 events was 6.2 km, and for the second group 5.3 km.

Figure 4 shows a fault-plane solution for the large (M = 4.5) event just before the main shock. First-motion data for this plot were taken from recordings of stations in Oregon, Washington and Nevada, as well as readings supplied by the University of California, Berkeley, for the northern California network. The solution is well-determined, and indicates a vertical fault striking N09°W; motion on this fault plane is dip-slip, with the west side down. The strike of this fault plane is almost identical to that of the focal plane in Figure 3, but the dips of the two planes are different. Unfortunately, first motions could not be read for the main shock because they were mixed with the coda of the foreshock.

The rate of occurrence of aftershocks decreased during the first month approximately as 1/t, based on 12-hour counts of events recorded by the ORV station (Figure 5).

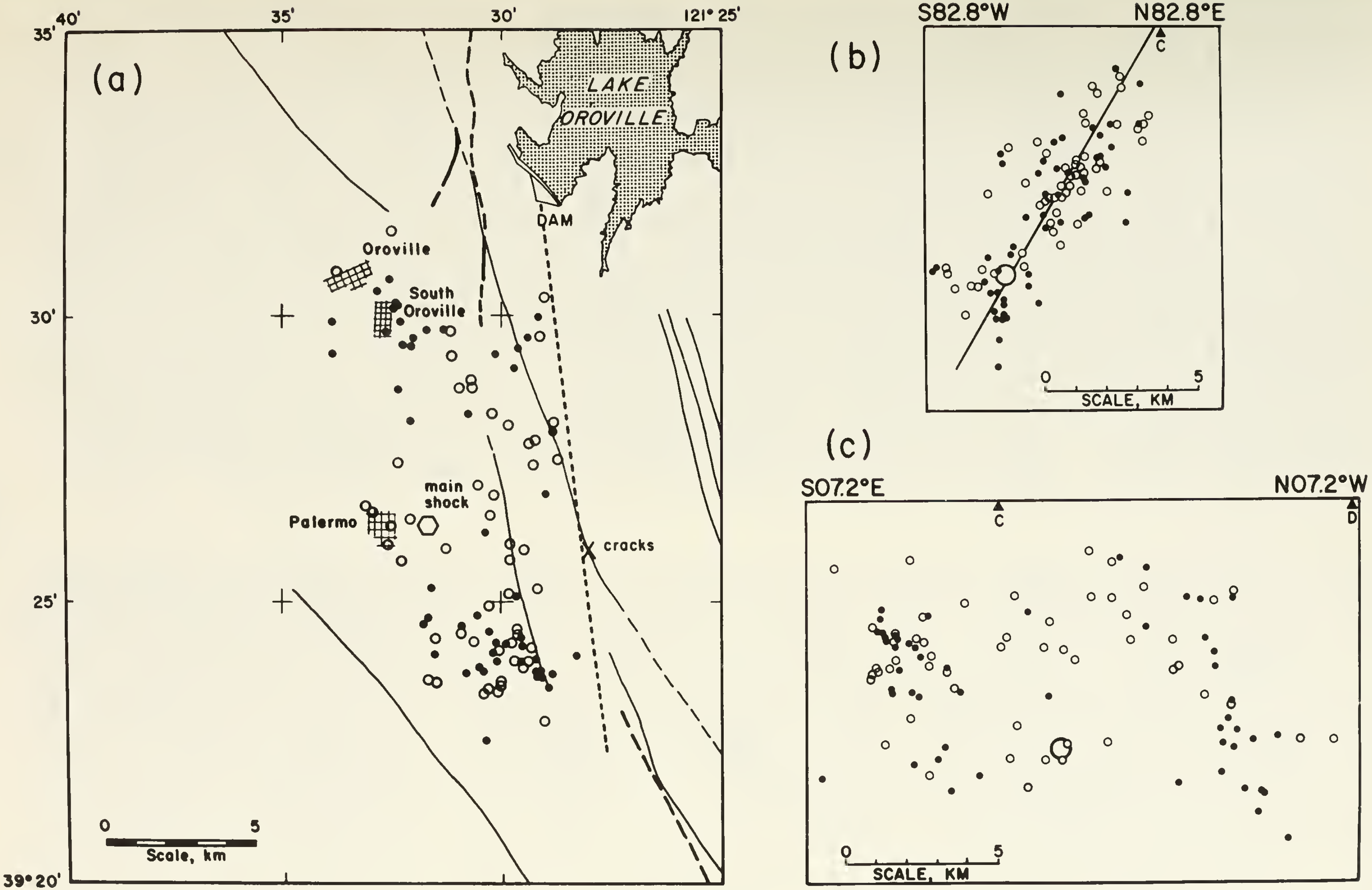

Figure 3. Distribution of foci. (a) Epicenter plot; (b) cross-section; (c) longitudinal section. Solid circles -- events prior to 08h on 8 August; open circles -- events after 08h on 8 August; heavy lines -- mapped faults; light lines -- lineaments from Skylab photograph; dotted line -- surface trace of plane fit by least-squares to focal coordinates. C -- location of surface cracking near Wyandotte; D -- location of Oroville Dam.

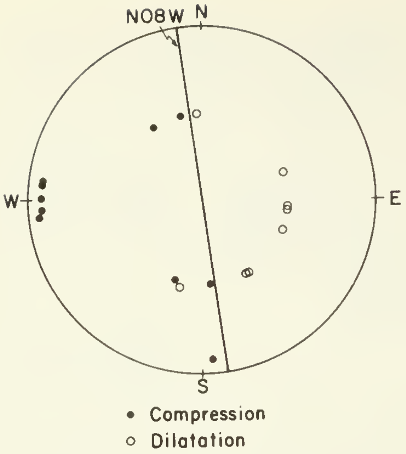

Figure 4. Focal mechanism of large foreshock. Lower-hemisphere projection.

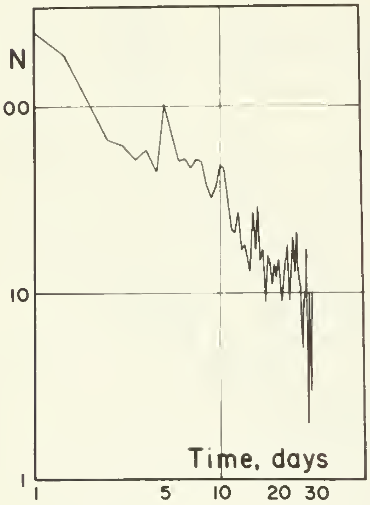

Figure 5. Plot of the number N of events recorded at station ORV in 12-hour intervals.

To estimate magnitude, event duration was measured from the ORV recordings for more than 2,000 aftershocks during August and September. We attempted to relate these duration measurements to magnitudes determined by the University of California, Berkeley (T. V. McEvilly, personal communication) but could not obtain a satisfactory relationship, for several reasons. The UCB magnitudes were based on different sets of data for different ranges of magnitude, and were not determined for events with $M < 1.6$. Since 80% of our data considered of events smaller than magnitude 1.6, we attempted to determine the slope of the duration/amplitude curve using amplitudes measured from our field redings. This indicated that, for small events ($M < 1.6$), $\log A = k + \log D$, where A and D are amplitude and duration, respectively, and k is a constant. However, the slope of 1.0 for the log A/log D curve for these small shocks did not agree with the slope of the M_L/log D curve for events larger than $M = 1.6$, the latter based on Berkeley magnitudes.

As an alternative, since M_L for the small Oroville events appears to be directly proportional to duration, we calculated LD, the logarithm of the duration in seconds for each event, and averaged these over samples of 100 events to look for changes during the sequence. The results, shown on Figure 6, suggest that $\overline{LD}$ decreased, from about 1.10 at the beginning of the sequence to 1.01 two months later. While these results are statistically only marginally significant, we believe they are worth mentioning in view of the rather steady trend toward lower $\overline{LD}$ values during the sequence. Since $\overline{LD}$ is in some way related to magnitude, this suggests that M also decreased during the two month period. From previous studies by Scholz (1968), Eaton, et al. (1970), Butovskaya and Kuznetsova (1971), and Hamilton (1972), this could be related either to a decrease in stress or a decrease in focal depth during the sequence.

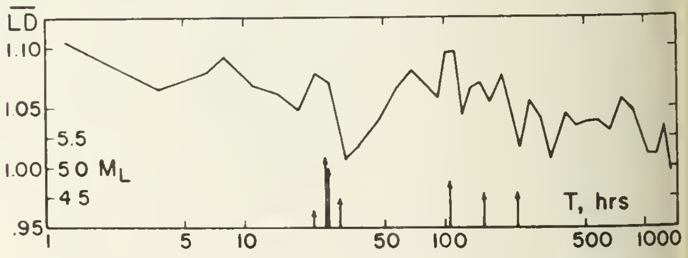

Figure 6. Plot of $\overline{LD}$ as a function of time. LD is logarithm of event duration (in seconds) on records of the ORV station, averaged over 100 events. Only events with $M < 4.0$ were included in the analysis. Arrows show time of occurrence of events with $M \leq 4.0$, with length of arrow proportional to M.

Recurrence curves, showing the cumulative number of earthquakes as a function of magnitude, are useful in comparing seismic characteristics of different areas. Such a curve was constructed for the Oroville sequence, using magnitudes supplied by T. V. McEvilly (personal communication) for 308 aftershocks. The straight-line portion of this curve, corresponding to the familiar relationship log N = a - b M, had a well-determined slope, or b-value, of 0.55. This is lower than those (0.8-0.9) generally found for earthquakes in the western Basin and Range, Sierra Nevada or Pacific Coastal regions. In previous studies, Scholz (1968) and Butovskaya and Kuznetsova (1971) have concluded that lower b-values may be associated with higher stress, or may occur in regions (or at depths in the crust) where the number of inhomogenieties per unit volume is relatively small.

The total energy of the aftershock sequence, calculated using the list of magnitudes supplied by T. V. McEvilly and Richter's (1958) relationship log E = 11.8 + 1.5 M, was 1.3 x 10^{20} ergs. This is approximately half the energy of the main shock; 90% of the aftershock energy was supplied by eight events with M > 4.5.

DISCUSSION

The Oroville earthquake sequence has a number of features in common with a sequence that occurred near Truckee, California, 130 km east of Oroville, in September, 1966. Ryall, et al. (1968) described the Truckee event and its aftershocks, and noted a correlation of aftershock occurrence with the solid-earth tides. Both earthquakes occurred several years after the filling of a nearby reservoir, although the reservoir at Truckee is very much smaller than Lake Oroville. Both main shocks had the same magnitude, and the distribution, depth and rate of decay of the two aftershock sequences were very similar. Differences between the two sequences were in magnitude of the largest aftershocks, b-value, focal mechanism and total energy in the aftershock sequence. Characteristics of the two sequences are compared in Table 1.

In most respects, both the Oroville and Truckee earthquakes had characteristics similar to other earthquake sequences in the western United States. For example, the size of the aftershock zone for Truckee and Oroville is similar to zones associated with main shocks of 5 1/2 - 6 at Caliente, Nevada in 1966 (Malone, 1968); Adel, Oregon in 1968 (Ryall and Savage, 1969); and Denio, Nevada in 1973 (Richins, 1974). For Oroville, the focal mechanism shown on Figure 4 is consistent with uplift of the Sierran block relative to the Great Valley; the Truckee mechanism is generally consistent with observed slip directions on the northeast-trending faults in the western Basin and Range region. The rate of aftershock decay for the two sequences is similar to that found for the 1966 Parkfield sequence by Eaton, et al. (1970), and is somewhat less than Richins' (1974) value for the 1973 Denio swarm. The average depth of focus (4-6 km) for Truckee and Oroville is greater than that (3-4 km) found by the U. S. Geological Survey for earthquakes induced by large underground explosions, slightly less than average depths of earthquakes in central California (5-7 km), and considerably less than average focal depths for the 1966 Caliente (6-9 km) and 1968 Adel (8-10 km) sequences. The b-value for Oroville is anomalously low, but that for Truckee is normal for western Basin and Range earthquakes.

Simpson (1975) reports that there are now over twenty cases where changes in seismic activity have been related to the filling of large reservoirs, but that there are also many large reservoirs where increased seismicity has not been observed. In the Oroville case, the possibility that the construction of the reservoir may have triggered the earthquake sequence is neither confirmed nor ruled out by our results. It is interesting that the main shock occurred shortly after a very rapid filling of the reservoir, and that the surface trace of a plane fit by least-

Table 1. Comparison of features of 1975 Oroville and 1966 Truckee earthquake sequence.

	Oroville	Truckee
Dam height, meters	210	42
Reservoir capacity, 10^6 m^3	4,364	37
Year reservoir filled	1968	1962
Year of maximum activity	1975	1966
Magnitude of main shock	5.7	5.7
Magnitude of largest aftershock	5.2	4.1
Focal mechanism of main shock	Normal (?)	Strike-slip
Average depth of aftershocks, km	5.8	4.6
Size of aftershock zone, km	11 x 17	11 x 11
Aftershock decay rate	$t^{-1.0}$	$t^{-.85}$
b-value	.55	.81
Total energy of aftershocks, ergs	1.3×10^{20}	10^{19}

squares to the zone of foci passes through the Oroville Dam (Figure 3a). In addition, the Oroville sequence has some features that appear to be common to reservoir-induced earthquakes: shallow focal depth, ratio of magnitudes of largest aftershock to main shock of about 0.9, magnitude of main shock less than 6. On the other hand, the earthquakes at Oroville share many characteristics with natural earthquake sequences in the western United States, and some features of the Oroville sequence do not agree with those reported for reservoir-induced shocks. These would include the low _b_-value, the fact that seismicity did not increase immediately following the construction of the reservoir (Hoffman, 1973), and the fact that the nearest distance from the focal zone to the dam (Figure 3c) is about 4 km.

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F. D. Ryall carried out the analysis of event durations and S-P times. A number of residents in the Oroville area assisted with our field operations, including Mr. and Mrs. Seldon Hicks, Mr. and Mrs. Buck Kabel, R. E. Sherwood, Fred Lorrain, and Mrs. C. K. Hallmark. W. F. Nicks, E. A. Broten, W. A. Peppin and B. M. Douglas of the University of Nevada assisted in the field work. This research was partly supported by the Advanced Research projects Agency and was monitored by the Air Force Office of Scientific Research under grant F44620-72-C-0069; it was also partly supported by a grant from the University of Nevada Research Advisory Board.

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THE OROVILLE EARTHQUAKE SEQUENCE OF AUGUST 1975

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Historically low regional seismicity continued through initial loading of Oroville Dam in 1967-68 and until the earthquake on June 28, 1975. Twenty-one foreshocks, the largest of magnitude 4.7, preceded the magnitude 5.7 main shock of 01 August. All foreshocks and aftershocks of $M_L \geq 3.0$ from June 28 to October 15, 1975, were located using seismographs operated by the University of California at Berkeley, USGS, and the California Department of Water Resources. The aftershock region covers an area approximately 14 km by 10 km southeast of the city of Oroville. The depth distribution of the earthquakes indicates a west dipping fault plane. The b value of 0.61 shows the sequence to be rich in larger magnitude aftershocks. The aftershock occurrence rate follows an Omori relation with $n(t) \propto t^{-.70}$. Apparent variability in the earthquake mechanisms of the series makes interpretation of composite fault plane solutions difficult, but the data indicate normal faulting striking NNW and west dip, the Sierra Nevada moving up with respect to the Great Valley.

INTRODUCTION

On August 1, 1975 at 2020 GMT(1320 PDT) a magnitude 5.7 earthquake occurred 12 km southwest of Oroville Dam (Figure 1) and caused some damage in the city of Oroville and vicinity. This earthquake was preceded by foreshocks beginning on June 28, 1975, the largest of which had $M_L = 3.5$ (Table 1); the sequence appeared to have died out (only five events between July 8 and August 1), when on August 1, 29 foreshocks with magnitude less than 4.8 occurred within five hours of the main shock.

OROVILLE DAM AND RESERVOIR

Construction of Oroville Dam, a zoned earthfill dam, and a key feature of the California Water Project, was finished in 1967. In November 1967 the final diversion tunnel was closed and water storage began. The gross operational storage capacity of Lake Oroville is slightly more than 3.5 million acre feet (4.4×10^9 m^3) at an elevation of 274 m above sea level. From base to crest, the dam is 235 m high with the crest elevation 281 m.

HISTORICAL SEISMIC ACTIVITY

The historical record indicates that the Oroville region is one of low seismicity. Figure 2 illustrates the seismicity in the region from 1851 to the present. The plotted earthquakes are selected from the complete seismicity record as those having designated intensities or magnitudes. Apparently the largest Modified Mercalli (MM) Intensity value affecting the city of Oroville between 1851 and August 1, 1975, was V, for the earthquake of January 24, 1875, probably centered immediately southwest of Oroville and reported felt as far away as Carson City, Nevada. The largest earthquake to affect the area was a magnitude 5.7 shock about 50 km north of Oroville on February 8, 1940. The instrumentally determined epicenters in Figure 2 are shown as solid circles. Earthquakes known from contemporary felt reports are indicated by the maximum MM intensity values.

MAGNITUDE ESTIMATE

The magnitude of the mainshock is estimated as 5.7 on the Richter scale.

This value was obtained by averaging the individual estimates from Wood-Anderson seismographs at Arcata, 5.7; Berkeley, 5.7; Stanford, 5.7 (T. Hanks personal communication); and Mount Hamilton, 5.6 (one component). No estimate was obtained from the instrument at Mineral as its recordings were off-scale.

The Richter magnitudes of the other earthquakes in Table 1 were obtained by averaging the individual values from Arcata (ARC), Berkeley (BKS), Mount Hamilton (MHC), and Mineral (MIN).

LOCATION OF THE EARTHQUAKES

The hypocentral parameters and Richter magnitudes of the 63 earthquakes ($M_L \geq 3.0$) of the Oroville sequence occurring between June 28 and October 15, 1975 are listed in Table 1. Locations of earthquakes between June 28 and August 16 are shown in Figure 1. Seismicity since August 16 has been typified by an extension of the aftershock zone to the north. The bars in the figure represent standard errors and the dashed diamonds indicate assumed locations. As a special check on the location of the main shock relative to its immediate foreshock, differential times between the respective P waves were measured using seismograms from 5 seismographic stations between 150 km and 300 km distant. The time difference between the first arrival of the magnitude 4.5 foreshock and the main event was 8.1 seconds at all azimuths observed. On this basis we conclude that the foreshock and mainshock locations are the same.

As indicated by the plots on Figure 1, the aftershock region covers an area approximately 10 km by 14 km centered 8 km southeast of Oroville. The earthquakes are generally deeper in the western part of the aftershock zone, with depths ranging from 1.5 to 11.4 km.

The epicenters for the entire sequence were estimated using P readings from 9 stations - Magalia (MGL), Oroville (ORV), Kanaka Peak (KPK), Butte City (BUT), Sutter Butte (SUT), Hobart Mills (HBM), St. Helena (SHC), Whiskeytown (WDC), and Jamestown (JAS) - incorporating station adjustments determined from well-recorded aftershocks.

EARTHQUAKE SEQUENCE CHARACTERISTICS

The Oroville sequence through August 11 consisted of 21 foreshocks, the main shock, and 292 aftershocks with Richter magnitude of 1.6 or above. The frequency of occurrence may be fitted to Omori's relation: $n(t) = A/(t+c)^p$ and the least-squares solution gave $p = 0.70 \pm 0.04$.

The equation $\log N = a - bM_L$ (N = cumulative number of earthquakes of magnitude greater than or equal to M_L) was fitted by least-squares and yielded $b = 0.61 \pm 0.01$. The low b value reflects the large proportion of big aftershocks in the sequence (there are 15 aftershocks with $M_L \geq 4.0$ through September 27).

First motion studies for twelve of the larger earthquakes reveal a faulting process of some complexity. Composite fault plane solutions show many inconsistent arrivals, but generally that the faulting involved is predominantly normal with NNW strike and west dip. The area east (Sierra Nevada) of the fault moved up with respect to the west (Great Valley).

ACKNOWLEDGMENTS

Data for this study were generously supplied by several individuals and groups. We are particularly grateful to Woody Savage (Woodward-Clyde Consultants), Charles Bufe (USGS), and Dave Kessler (DWR). Professors Bruce Bolt and Thomas McEvilly offered valuable suggestions and criticism.

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TABLE I - EARTHQUAKE DATA FOR EVENTS WITH $M_L \geq 3.0$

	Date	Origin Time (OT)	σ(T)sec	Magnitude M_L	Latitude φ	σ(φ)km	Longitude λ	σ(λ)km	Depth h	σ(h)km
1	28 JUN 75	041953.72	0.13	3.5	39°28.33'	1.19	121°31.45'	1.05	7.56km	1.59
2	01 AUG 75	154537.81	0.07	3.8	39 26.98	0.67	121 31.87	0.67	7.27	1.06
3	01 AUG 75	162717.81	0.14	4.7	39 26.29	1.19	121 32.25	1.20	4.89	2.17
4	01 AUG 75	172650.12	0.09	3.0	39 27.71	0.85	121 32.27	0.83	8.57	1.22
5	01 AUG 75	202004.75	0.08	4.5	39 26.33	0.76	121 31.71	0.76	8.01	1.17
6	01 AUG 75	202012.85		5.7	39 26.33		121 31.71			
7	01 AUG 75	2025		4.7	39 26.33		121 31.71			
8	01 AUG 75	2029		4.6	39 25.33		121 31.71			
9	01 AUG 75	203239.84	0.15	3.0	39 26.71	1.62	121 30.40	1.64	4.82	3.21
10	01 AUG 75	2037		3.5	39 26.71		121 30.40			
11	01 AUG 75	2045		3.0	39 26.71		121 30.40			
12	01 AUG 75	204618.40	0.14	3.8	39 28.40	1.56	121 30.02	1.59	6.13	2.69
13	01 AUG 75	210539.84	0.04	3.0	39 25.98	0.38	121 29.25	0.43	6.74	0.63
14	01 AUG 75	212150.65	0.07	4.1	39 26.53	0.64	121 31.70	0.64	7.76	0.99
15	01 AUG 75	212559.02	0.04	3.3	39 28.44	0.42	121 31.08	0.41	7.08	0.63
16	01 AUG 75	212924.12	0.08	3.6	39 27.12	0.69	121 32.92	0.80	6.55	1.21
17	01 AUG 75	234440.98	0.03	3.4	39 29.18	0.25	121 31.34	0.24	7.51	0.35
18	02 AUG 75	005248.47	0.03	3.8	39 29.06	0.25	121 30.55	0.24	7.27	0.36
19	02 AUG 75	063157.19	0.06	3.2	39 26.84	0.50	121 29.01	0.38	5.68	0.79
20	02 AUG 75	101153.68	0.04	3.1	39 29.40	0.37	121 30.70	0.35	7.22	0.52
21	02 AUG 75	104900.12	0.07	3.3	39 25.66	0.52	121 28.41	0.43	5.54	0.85
22	02 AUG 75	115150.74	0.12	3.4	39 28.36	0.89	121 29.30	0.91	2.49	1.86
23	02 AUG 75	144438.71	0.04	3.2	39 25.03	0.32	121 29.38	0.33	5.00	0.59
24	02 AUG 75	165145.11	0.05	3.7	39 25.07	0.43	121 29.09	0.44	6.48	0.75
25	02 AUG 75	172429.23	0.07	4.3	39 28.42	0.60	121 28.25	0.59	5.84	0.98
26	02 AUG 75	174324.13	0.06	4.0	39 28.66	0.51	121 28.41	0.49	5.52	0.83
27	02 AUG 75	195636.85	0.05	3.1	39 26.89	0.44	121 32.20	0.44	7.10	0.70
28	02 AUG 75	202716.32	0.05	5.1	39 26.69	0.35	121 27.76	0.36	3.62	0.71
29	02 AUG 75	203548.55	0.06	3.9	39 28.26	0.52	121 28.89	0.51	5.98	0.84
30	02 AUG 75	205855.70	0.06	3.8	39 25.93	0.50	121 27.97	0.51	5.71	0.90
31	02 AUG 75	2059		5.2	39 25.93		121 27.97			
32	02 AUG 75	214001.34	0.07	3.9	39°25.62'	0.57	121°28.39'	0.58	5.39	1.04
33	03 AUG 75	010305.77	0.04	4.6	39 29.26	0.40	121 31.06	0.38	7.98	0.55
34	03 AUG 75	024708.80	0.04	4.1	39 28.68	0.33	121 30.06	0.32	6.79	0.50
35	04 AUG 75	094745.01	0.06	3.5	39 25.27	0.61	121 31.36	0.45	7.57	0.55
36	05 AUG 75	022857.35	0.05	3.3	39 24.91	0.39	121 29.46	0.33	7.17	0.63
37	05 AUG 75	204424.50	0.17	3.2	39 24.87	1.35	121 30.87	1.15	6.79	2.23
38	06 AUG 75	035029.94	0.20	4.7	39 28.73	1.94	121 31.46	1.73	7.69	2.52
39	06 AUG 75	162547.93	0.14	3.1	39 26.73	1.24	121 27.58	1.14	6.49	1.30
40	06 AUG 75	164152.08	0.02	3.6	39 29.80	0.17	121 31.76	0.17	8.40	0.15
41	06 AUG 75	210033.46	0.11	3.0	39 26.37	0.95	121 29.10	0.89	9.20	0.98
42	06 AUG 75	2100		3.0	39 26.37		121 29.10			
43	07 AUG 75	203120.38	0.15	3.1	39 30.99	1.56	121 31.98	1.49	8.68	1.71
44	08 AUG 75	070050.09	0.05	4.9	39 30.13	0.51	121 30.72	0.46	7.64	0.62
45	08 AUG 75	133753.87	0.08	3.2	39 29.79	0.70	121 29.37	0.64	6.29	0.68
46	08 AUG 75	190327.23	0.09	3.1	39 23.60	0.65	121 29.60	0.62	5.60	0.91
47	09 AUG 75	073847.48	0.10	3.0	39 24.80	0.74	121 29.00	0.70	7.46	0.93
48	11 AUG 75	024016.73	0.35	3.0	39 27.72	2.29	121 26.53	1.95	1.52	3.89
49	11 AUG 75	061136.34	0.12	4.3	39 26.78	0.91	121 28.85	0.91	4.26	1.24
50	11 AUG 75	155905.26	0.19	3.6	39 28.22	1.40	121 33.23	1.39	6.39	1.68
51	16 AUG 75	054809.39	0.03	4.0	39 28.33	0.33	121 31.26	0.40	9.01	0.51
52	23 AUG 75	183153.26	0.13	3.1	39 29.90	1.20	121 29.64	1.14	4.96	1.74
53	24 AUG 75	091037.72	0.16	3.3	39 30.48	1.78	121 29.94	1.32	5.26	2.20
54	25 AUG 75	133511.65	0.13	3.2	39 20.36	1.12	121 30.60	1.25	3.87	1.90
55	05 SEP 75	210139.22	0.12	3.2	39 24.79	0.99	121 31.35	1.17	7.15	1.65
56	10 SEP 75	173905.17	0.07	3.4	39 31.21	0.68	121 32.24	0.85	6.33	1.03
57	12 SEP 75	020047.89	0.03	3.5	39 30.14	0.27	121 29.19	0.27	3.62	0.39
58	26 SEP 75	023107.14	0.29	4.0	39 30.00	1.05	121 29.76	2.06	11.44	1.35
59	27 SEP 75	223438.05	0.03	4.6	39 30.65	0.33	121 32.19	0.42	8.44	0.46
60	27 SEP 75	230430.94	0.02	3.1	39 31.05	0.17	121 31.09	0.20	5.39	0.21
61	27 SEP 75	232805.02	0.12	3.2	39 30.93	1.17	121 33.21	1.51	7.07	1.83
62	28 SEP 75	210715		3.4	39 31		121 32			
63	10 OCT 75	074447.63	0.01	3.6	39 27.44	0.06	121 29.12	0.07	3.14	0.22

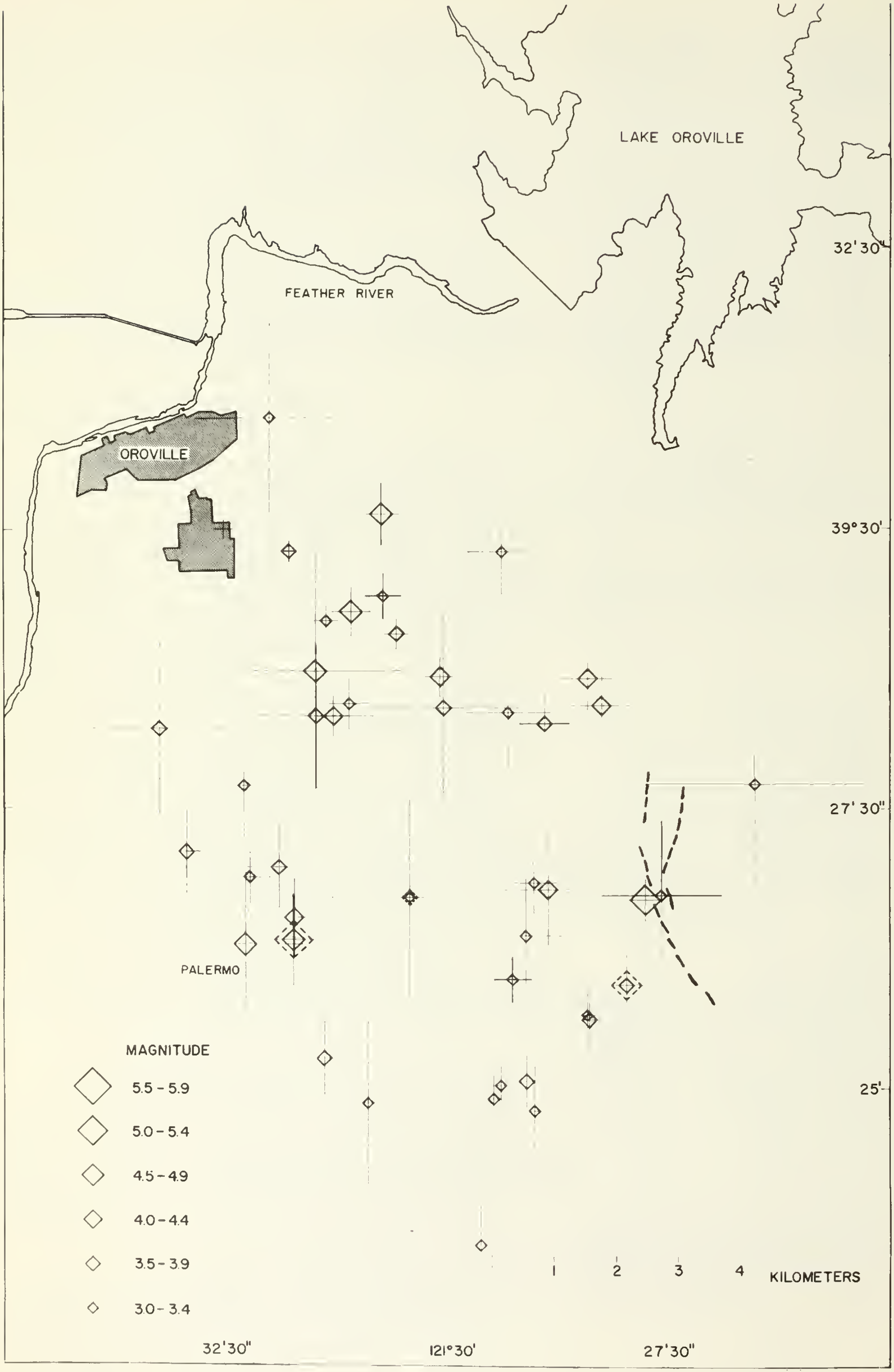

Figure 1: Earthquake locations of the Oroville sequence. Standard errors in location estimated by least squares are indicated by bars through the epicenters. Dashed diamonds represent earthquakes whose location is assumed to be that of its immediate foreshock. The dashed lines indicate the lines of surface cracks observed after the mainshock (Jack Marlette), personal communication).

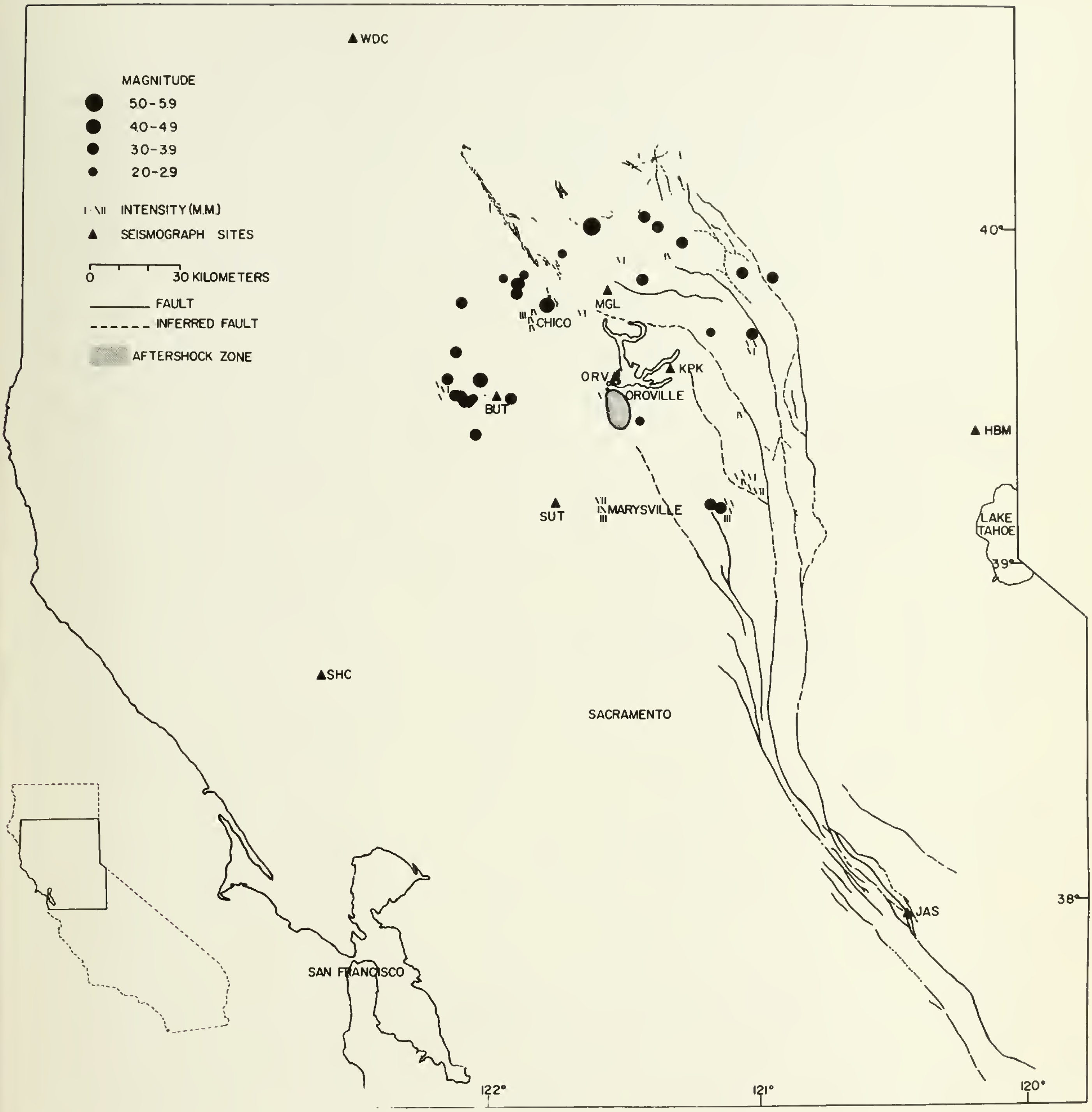

Figure 2: Station locations and historical seismicity within 60 km of Oroville.

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